FACULTAD DE MEDICINA Y CIRUGÍA

Departamento de Medicina y Cirugía

Programa de Doctorado: Medicina y Cirugía

Universidad Autónoma de Madrid

TESIS DOCTORAL

Evaluación y Análisis Comparativo de los Efectos de los Métodos de Representación de Movimiento en el Proceso de Aprendizaje Motor

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Madrid, 2021

Per a les persones que m'estimen

AGRADECIMIENTOS

Me gustaría comenzar este apartado de agradecimientos dando las gracias a todas las personas, tanto pacientes, como personas asintomáticas, que han querido desinteresadamente participar en las investigaciones subyacentes a la presente tesis doctoral, haciéndola posible. Gracias de corazón.

En segundo lugar, quisiera dar las gracias a mis dos directores de tesis, el profesor Dr. Roy La Touche y el profesor Dr. Jose Vicente León Hernández.

Al Dr. La Touche tengo muchas cosas que agradecerle donde la mayoría, van más allá de este proyecto de tesis doctoral. Son muchos años los que llevo a su lado desde que era su alumno de grado hasta la finalización de este proyecto, también como alumno. Roy me ha acompañado en este viaje académico y personal de múltiples etapas dándome los mejores consejos que una persona puede dar a sus alumnos. Roy enfatiza y ensalza valores tan importantes como el trabajo diario, la humildad, el respeto, el amor y la dedicación hacia el trabajo.

Roy integra, comprende e intenta hacerte ver distintos puntos de vista de la realidad, siempre enfocados a reorganizar las interpretaciones negativas de los retos académicos, pero sobre todo los retos y los problemas de la vida, para así transformarlos en oportunidades. Ha sido un privilegio para mí haberle conocido y estas pequeñas líneas son para él, como profesor, como compañero de trabajo y como amigo. Gracias por todo Roy, necesitaría el volumen de, mínimo, otras 10 tesis como esta para intentar plasmar todo el aprecio y todo el cariño y la admiración que te tengo. Gracias por todo.

Por otro lado, y no menos importante, se encuentra el Dr. León Hernández. Jose Vicente es el director de tesis doctoral que todo doctorando querría tener. Es una persona rigurosa, humilde, cercana, trabajadora, con una vocación hacia la investigación

superlativa. Una persona que te motiva, que te hace pensar, con un potencial muy elevado y me gustaría darle las gracias por todo lo que ha aportado a esta tesis doctoral, por todo lo que me ha aportado como profesor, como compañero y, sobre todo, como amigo. Gracias por todo Jose, siempre te estaré agradecido por toda tu ayuda, por todo tu trabajo desinteresado y por ser la persona que eres. Muchísimas gracias.

A la siguiente persona que quiero agradecer es a Luis Suso. Luis ha sido una persona fundamental desde que nos conocimos en el inicio del grado. Han sido horas, días y años de pasar tiempo juntos trabajando con el objetivo de salir hacia delante dentro de una difícil profesión altamente castigada desde dentro y desde fuera de la misma. Hemos pasado los mejores y los peores momentos juntos, pero nunca y, sobre todo, por nada, esta amistad se ha roto, ni siquiera se ha mínimamente erosionado. Esta es una amistad estable y consistente. Gracias Luis por tu trabajo constante, por tu ayuda, por todo lo que hemos pasado y por todo lo que nos viene ahora. La capital del Turia está en deuda con nosotros todavía. Gracias, de corazón.

Llegados a este punto, y dejando a un lado el ámbito académico, me gustaría dar las gracias a las cuatro personas que más quiero y más querré en este extraño mundo que nos tocó habitar. Me gustaría dar las gracias a mi madre María José, a mi padre Fernando, a mi hermana Paula y a mi abuela Fina. No puedo dividir los agradecimientos porque siempre hemos sido un todo, indestructible, siempre los cinco. Va a ser imposible plasmar todo el amor que tengo hacia ellos en unas pequeñas líneas, pero si he llegado hasta aquí, habrá que intentarlo, aunque no sé cómo empezar.

Mi familia siempre ha estado a mi lado en todo aquello que me he propuesto; si estaba en Valencia, hacia allá que iban para poder verme; si estaba en Madrid, hacia Madrid que venían también; si me hubiera ido a la luna, a la luna que hubieran ido sin pensarlo ni un segundo. Ese amor indescriptible, incondicional, verdadero, sincero ha estado presente en mi vida desde que tengo consciencia de estar vivo y lo seguirá estando hasta el fin de los días.

Mis padres y mi abuela siempre se han privado de sus cosas para así ofrecernos, tanto a mi hermana como a mí, las mejores oportunidades cuando la vida así lo imponía. Ellos nunca han sabido muy bien qué estaba haciendo durante esta tesis doctoral, —siguen sin saberlo— pero siempre han estado para darme lo mejor, sin importarles lo que fuera. No hay día que pase que no agradezco a la vida el haber tenido la suerte de poder tener unos padres, una abuela y una hermana así; ellos han sido, son y serán lo mejor de mi vida siempre. Tengo ganas de volver a Valencia por estar más tiempo con ellos, por verlos más y mejor, y porque no hay un lugar allí que no actúe como un estímulo condicionado elicitando en mí, un recuerdo suyo. Gràcies mama, papa, iaia i teta, gràcies de veritat.

Además de mi familia, tengo que dar las gracias a mi otra familia; mis amigos. Ellos lo son todo para mí: Amadeo, Teresa, Ferran, Alba, Carlos, Andrea, María Climent, María Gómez, Rosa Belén, Alba y Cata. Gracias por entender mi ausencia estos años, gracias por escuchar mis penas cuando estábamos de cañas, o de copas y, sobre todo, gracias por estar y formar parte de mi vida. Gracias también de corazón. Sin vosotros, esto no habría podido ser posible.

No podría terminar este apartado de agradecimientos sin mencionar a otra persona importante. Él es Mario Romero Palau. Mario me ha ayudado muchísimo estos años y es la persona que hace posible que la Psicología, la cual es uno de los pilares fundamentales de mi vida, siga presente en esta. Mario es una persona trabajadora, sincera, hambrienta de conocimiento la cual, será uno de los psicólogos más influyentes de este país en los próximos años. Siempre le estaré agradecido por todo lo que ha hecho y sigue haciendo por mí. Gracias por todo. Siempre estaré en deuda contigo. Gracias, amigo.

Finalmente, me gustaría dar las gracias a todos los profesores y profesoras de la Universitat de València i del Centro Superior de Estudios Universitarios (CSEU) La Salle que han pasado por mi vida formándome como profesional, pero sobre todo como persona, especialmente de esta última, me gustaría hacerles un pequeño homenaje a algunas personas que han sido muy importantes e influyentes para mí con estas pequeñas líneas:

Al Dr. Sergio Lerma Lara por confiar en mí siempre, en cualquier ámbito (clínico, académico, investigación, etc.), y por ser el mejor docente que he tenido en mi vida; a la Dra. Alba Paris Alemany, por darme la oportunidad de trabajar a su lado. Alba es una persona sincera, trabajadora, inteligente, cercana… trabajar con ella es una de las mejores cosas que me han pasado en la vida; al Dr. Josué Fernández Carnero por ser la persona con el corazón más grande de toda Madrid y por compartir un conocimiento que necesitaríamos vidas para poder llegar a tener. Siempre estaré agradecido el poder haberle tenido como profesor y ahora, como compañero y amigo. Gracias Josué. Agradecer también al Dr. Raúl Ferrer Peña por su ayuda desinteresada siempre que la he necesitado; al profesor Alberto García Muntión por ser tan buena persona y por ser el mejor compañero de trabajo que una persona podría tener; al Dr. Óscar Yepes Rojas por su calidez humana y por poder disfrutar de todo su inmenso conocimiento durante estos años; al Dr. Héctor Beltrán Alacreu por sus consejos y por sus charlas, a Mónica Grande Alonso, la persona que más tiempo he pasado en el CSEU. También agradecer todas las palabras y toda la ayuda del Dr. Daniel Muñoz y el Dr. Ibai López. Para finalizar, me gustaría agradecer de manera especial a mi compañero y amigo el Dr. Joaquín Pardo Montero, al cual le estaré siempre agradecido por transmitirme su pasión por la

Psicología. Gracias por todo doctor, gracias a usted mi vida es más completa y yo soy más feliz. Gracias, amigo.

Finalmente, y no menos importante, me gustaría dar las gracias al profesor Santiago Angulo por ser un docente excelente, por su inconmensurable ayuda en el estudio más importante de mi carrera académica e investigadora y por ayudarme a comprender bien la estadística en las ciencias de la salud, algo que me hará estar en deuda con él durante el resto de mi vida. Gracias Santiago.

Gracias a todos y todas por este viaje tan duro pero tan bonito. Soy lo que soy gracias a vosotros y vosotras. Gracias de corazón.

Y ahora sí, para finalizar me gustaría agradecer especialmente al CSEU La Salle por toda la ayuda prestada en diversos aspectos no comentados hasta el momento como los servicios de edición de manuscritos, el uso de sus instalaciones, las oportunidades para crecer profesionalmente, por todo. Para mí, es y será siempre el mejor Centro Universitario de este país, al menos para estudiar Fisioterapia. Una calidad humana superlativa y una forma de trabajar maravillosa, entendiendo a sus trabajadores como personas con sus sentimientos, sus cogniciones, sus motivaciones, sus percepciones de realidad, de justicia, etc. Siempre llevaré conmigo todo lo bueno que recibí de vosotros. Gracias, gracias y mil veces gracias.

ÍNDICE GENERAL

RESUMEN

Introducción: El estudio del aprendizaje motor es fundamental en distintas áreas de interés, tales como la rehabilitación, las ciencias del deporte, la música, el ocio o incluso la comunicación y el lenguaje. Los resultados de algunas investigaciones recientes en esta línea han mostrado que el entrenamiento de observación de acciones parece que conduce hacia un mayor aprendizaje motor en comparación con la imaginería motora aunque solamente se ha evaluado a muy corto plazo. Sin embargo, y a pesar de estas investigaciones, consideramos que todavía es necesario contar con un mayor número de estudios que evalúen estos hallazgos. La evidencia científica más actual nos ha llevado a la reflexión sobre las limitaciones que existen actualmente con relación a los métodos de representación de movimiento sobre el proceso neurofisiológico de aprendizaje motor. A través de esta tesis doctoral, se ha intentado dar respuestas a diversos interrogantes, ampliando y profundizando en aspectos todavía desconocidos y no reportados en el actual estado del arte.

Objetivo general: El objetivo general de las investigaciones que conforman esta tesis doctoral fue evaluar y comparar los efectos de los métodos de representación de movimiento, a través de la observación de acciones y de la imaginería motora, en el proceso de aprendizaje motor en distintas poblaciones de interés, así como en distintos momentos temporales.

Métodos: Se llevaron a cabo un total de cinco estudios. Dos de ellos fueron ensayos controlados aleatorios a simple ciego. Estos dos estudios fueron realizados en población asintomática. Uno de ellos comparó los métodos de representación de movimiento en combinación con el entrenamiento físico mientras que en el otro estudio, se evaluaron los efectos de los métodos de representación de movimiento de manera aislada y

además, se llevó a cabo un seguimiento hasta los 4 meses tras finalizar la intervención, evaluándose las medidas de resultado incluidas al finalizar, a la semana, al primer mes y al cuarto mes de seguimiento. En adición a esto, el tercer estudio fue un ensayo clínico aleatorizado a simple ciego en pacientes con dolor de cuello crónico no específico. En este estudio también se aislaron los métodos de representación de movimiento para evaluar la fase rápida del aprendizaje motor a través de la evaluación del sentido de reposicionamiento articular cervical tras la representación de dos ejercicios de control sensoriomotor cráneo-cervical. En cuarto lugar, se realizó una hipótesis neurofisiológica, con perspectiva bioconductual, junto con una revisión narrativa de la literatura con el objetivo de establecer una construcción teórica, específicamente, de las diferencias posibles en el proceso de creación de las representaciones mnémicas y, por tanto, del proceso de integración de la información visual en la formación de la memoria motora como prerrequisito del aprendizaje motor. Para finalizar, se llevó a cabo una revisión sistemática y meta-análisis con el objetivo de evaluar el impacto de los métodos de representación de movimientos sobre procesos de reaprendizaje y reacondicionamiento motor durante los procedimientos de inmovilización experimental en sujetos sanos, en pacientes con lesiones que no requirieron cirugía y en procesos quirúrgicos que requirieron o no inmovilización.

Resultados: En la evaluación y comparación directa de los resultados obtenidos por los métodos de representación de movimiento a través del entrenamiento de observación de acciones e imaginería motora, se presentaron los siguientes hallazgos: 1) El entrenamiento de observación de acciones, en adición a unas tareas de control sensoriomotor lumbo-pélvico, condujo a un proceso de aprendizaje motor con mayor rapidez en comparación a no incluirlo. Sin embargo, este cambio no fue significativamente superior a los encontrados durante la aplicación de la imaginería motora; 2) A nivel clínico, tanto el entrenamiento de observación de acciones, como la imaginería motora, ambas formas de manera aislada, fueron significativamente superiores a una intervención placebo conduciendo a un proceso de aprendizaje motor en la región cráneo-cervical en pacientes con dolor de cuello crónico no específico; 3) La observación de acciones condujo a un mayor proceso de aprendizaje motor hasta al menos 4 meses en posiciones manuales sencillas y hasta 1 mes en posiciones manuales complejas en comparación con la imaginería motora, ambas de manera aislada. Ambas formas fueron significativamente superiores a la intervención placebo en el corto/medio plazo. La imaginería motora nunca fue estadísticamente superior al entrenamiento de observación de acciones; 4) El entrenamiento de observación de acciones obtuvo resultados significativamente superiores con respecto al mantenimiento del estado funcional y del equilibrio en la comparación con el tratamiento habitual de manera aislada en pacientes postquirúrgicos; 5) La imaginería motora de manera aislada mostró resultados significativos en cuanto al mantenimiento de la fuerza y del rango de movilidad en sujetos sanos inmovilizados experimentalmente. Además, los resultados también mostraron que la imaginería motora, en combinación con un tratamiento habitual, provocó un mantenimiento significativamente mayor de la fuerza y de la velocidad de la marcha en los pacientes que se sometieron a una cirugía sin inmovilización, pero no con respecto al rango de movimiento. Finalmente, tampoco se encontraron resultados significativos en el mantenimiento de la fuerza después de una cirugía seguida de un proceso de inmovilización.

Conclusiones: Las principales conclusiones derivadas del conjunto de estudios que conforman esta tesis doctoral son que, tanto el entrenamiento de observación de acciones, como la imaginería motora, de manera aislada, son capaces de conducir a un proceso de aprendizaje motor. Parece que el entrenamiento de observación de acciones provoca mayores cambios, así como más duraderos, hasta el corto/medio plazo, en comparación con la imaginería motora si se aplica de manera aislada y además, parece que aprendizaje motor mediado por la observación de acciones es más sólido y robusto. Sin embargo, si los métodos de representación de movimiento se combinan con el ejercicio físico, los hallazgos muestran que ninguna técnica es superior a la otra, pero la combinación de ambas con el ejercicio real sí provoca cambios superiores al ejercicio real aplicado exclusivamente sin los métodos de representación de movimiento. Con respecto a la neurofisiología subyacente a los métodos de representación de movimiento, sugerimos que el entrenamiento de observación de acciones es una herramienta más eficiente que la imaginería motora en la generación de representaciones mnémicas de los movimientos como prerrequisito al aprendizaje, y a su vez, es menos demandante, en términos de carga cognitiva, haciéndola más robusta y menos susceptible a la influencia de las variables relacionadas con la construcción y generación de imágenes de movimiento. Para finalizar, los métodos de representación del movimiento han mostrado tener un impacto significativo en la mejora de diversas variables motoras en particular, y en el mantenimiento de la condición física en general, previniendo y minimizando así el desaprendizaje y el desacondiconamiento motor durante los procesos de inmovilización experimental en individuos sanos, en pacientes con lesiones que no requirieron cirugía y en pacientes postquirúrgicos que requirieron o no inmovilización.

Lista de Publicaciones Originales y Estudios

La presente tesis doctoral está basada en la siguiente lista de 4 publicaciones originales y 1 estudio de meta-análisis los cuales, forman parte de una línea de investigación que versa sobre el aprendizaje motor tanto en población clínica, como en sujetos sanos. Los datos hallados en las presentes investigaciones se presentan de forma completa en el apartado ‘resultados’.

1. **Cuenca-Martínez F**, Suso-Martí L, Sánchez-Martín D, Soria-Soria C, Serrano-Santos J, Paris-Alemany A, La Touche R, & León-Hernández JV. Effects of motor imagery and action observation on lumbo-pelvic motor control, trunk muscles strength and level of perceived fatigue: a randomized controlled trial, *Research Quarterly for Exercise and Sport*. 2020; 91(1): 34-46. DOI: 10.1080/02701367.2019.1645941

   Número Comité Ética: CSEULS-PI-019/2019

   Factor de Impacto: 1,883; Q3 (47/85); Percentil 45,29.

2. **Cuenca-Martínez F**, La Touche R, León-Hernández JV, & Suso-Martí L. Mental practice in isolation improves cervical joint position sense in patients with chronic neck pain: A randomized single-blind placebo trial, *PeerJ*. 2019; 7: e7681. DOI: 10.7717/peerj.7681

   Factor de Impacto: 2,379; Q2 (32/71); Percentil 55,63.

   Número Comité Ética: CSEULS-PI-027/2019

3. **Cuenca-Martínez F**, Suso-Martí L, León-Hernández JV, & La Touche R. Effects of movement representation techniques on motor learning of thumb-opposition tasks, *Scientific Reports*. 2020; 10(1): 12267. DOI: 10.1038/s41598-020-67905-7

   Factor de Impacto: 3,998; Q1 (17/71); Percentil 76,76.

   Número Comité Ética: CSEULS-PI-013/2019

4. **Cuenca-Martínez F**, Suso-Martí L, León-Hernández JV, & La Touche R. The Role of Movement Representation Techniques in the Motor Learning Process: A Neurophysiological Hypothesis and a Narrative Review, *Brain Sciences*. 2020; 10(1): 27. DOI: 10.3390/brainsci10010027

   Factor de Impacto: 3,332; Q2 (113/271); Percentil 58,48.

5. **Cuenca-Martínez F**, Angulo-Díaz-Parreño S, Feijóo-Rubio X, Fernández-Solís MM, León-Hernández JV, La Touche R & Suso-Martí L. Motor Effects of Movement Representation Techniques and Cross-Education Training in Recovery and Immobilization Processes: A Systematic Review and Meta-Analysis.

   (Estudio en revisión)

-Factor de Impacto acumulado: **11,593**

-Distribución de los artículos por cuartiles:

1 artículo en Q1

2 artículos en Q2

1 artículo en Q3

Abreviaturas

DCCI: Dolor de cuello crónico inespecífico

EVA: Escala visual analógica

GC: Grupo control

GP: Grupo placebo

IC: Intervalo de confianza

IM: Imaginería motora

MIQ-R: Cuestionario revisado de imagen del movimiento

OA: Observación de acciones

SMD: Diferencia de medias estandarizada

SRA: Sentido de reposicionamiento articular

TGSD: Teoría general de sistemas dinámicos

INTRODUCCIÓN

1. Introducción

1.1 Métodos de Representación de Movimiento: Entrenamiento de Observación de Acciones e Imaginería Motora

1.1.1 Definición y principales características

Los métodos de representación de movimiento, conocidos en inglés como *movement representation techniques*, *mental practice*, *mental training*, *symbolic rehearsal*, *movement/motor simulation o covert rehearsal*, comprenden un amplio grupo de herramientas de construcción y creación de imágenes motoras que precisan de un carácter activo y dinámico de representación y de procesamiento de la información (Munzert et al., 2008).

Los métodos de representación de movimiento han supuesto una revolución en el campo de la neurociencia cognitiva, así como en la psicología experimental y del deporte (Guillot & Collet, 2008; Isaac, 1992). Esto es debido a su potencial en diferentes campos de la rehabilitación, tales como en el campo de la rehabilitación neurológica, en el campo del dolor crónico o en el ámbito deportivo. Los métodos de representación de movimiento pueden aplicarse en combinación con la práctica real (Allami et al., 2008; La Touche et al., 2019; Losana-Ferrer et al., 2018), o de manera aislada (Frenkel et al., 2014; Suso-Martí et al., 2019).

Por un lado, una representación es un estado físico que ofrece una referencia en relación a una entidad (un objeto, un suceso, un caso) o bien, a una característica la cual contiene un modelo de codificación (una imagen, una acción, una metáfora) y abarca además, un argumento que comunica la misma en términos de significado (Goldstein, 2011). En adición a esto, un mismo contenido, tema, razonamiento o tesis es capaz de propagarse en distintas dimensiones (verbal, visual estática o dinámica, auditiva, de manera combinada, etc.) (Goldstein, 2011).

Por otro lado, el término procesamiento hace referencia al proceso de modulación de una información de llegada dada para producir una distinta respuesta de salida. La construcción de imágenes motoras, requieren de un sistema de procesamiento de la información para poder llevarse a cabo, el cual, es ampliamente complejo y requiere de múltiples interacciones para poder realizarse (Goldstein, 2011).

Dos de los métodos de representación de movimiento más estudiados y presentes en la literatura científica son la imaginería motora (de aquí en adelante, IM) y el entrenamiento de observación de acciones (OA). Decety (1996) estableció las bases neurofisiológicas de la IM, la cual, fue definida como la capacidad o habilidad cognitiva y dinámica, que implica la representación o construcción de un gesto motor, de manera interna, prescindiendo de su ejecución real motora (Decety, 1996). Por otro lado, Buccino (2014), definió el entrenamiento de OA como la representación interna del conjunto de movimientos reales evocada por aquello visualizado, en directo, por el espectador (Buccino, 2014).

En base al actual estado del arte, ambos métodos de representación de movimiento producen una activación de las regiones cerebrales relacionadas con la planificación, generación, ajuste y automatización del movimiento voluntario de manera muy similar que cuando la acción acontece de manera real (Lotze et al., 1999; Taube et al., 2015). Sin embargo, se ha reportado que esta actividad cerebral es mayor durante la ejecución real del gesto motor voluntario en comparación con la representación de movimiento (Miller et al., 2010). De hecho, el propio Miller y su grupo de investigación, encontraron que la magnitud de la actividad cortical, inducida por la IM, provocaba una activación en la corteza cerebral aproximadamente del 25% del total provocado por la ejecución real del movimiento voluntario (Miller et al., 2010), aunque es probable que este porcentaje pueda variar en función de algunas variables como el tipo de gesto motor utilizado, la capacidad de generar imágenes de movimiento, el esfuerzo empleado en la tarea, la viveza en el proceso de construcción de la imagen motora, los niveles de actividad física, entre otros.

En adición a esto, también han sido estudiadas las similitudes y las diferencias entre los dos métodos de representación de movimiento a nivel neurofisiológico. Munzert et al. (2008) encontraron, mediante estudios de neuroimagen a través de resonancia magnética funcional, un solapamiento en la activación cerebral de ambos métodos de representación de movimiento en la corteza motora primaria, la corteza premotora, el área motora suplementaria, el surco intraparietal, ambos hemisferios cerebelosos y ciertas zonas de los ganglios de la base. Sin embargo, Munzert et al. (2008) también encontraron que la IM, provocaba una activación mayor en la ínsula posterior y en la corteza cingulada anterior en comparación al entrenamiento de OA, pero este, mostró una activación mayor a la IM en la activación del hipocampo, el lóbulo parietal superior y algunas áreas del cerebelo.

En adición a esto, Hardwick et al. (2018) llevaron a cabo una síntesis cuantitativa de toda la literatura científica disponible para evaluar la citada superposición de la actividad de las áreas cerebrales durante la IM, la OA y la ejecución real. Encontraron que la IM y el entrenamiento de OA reclutaron redes corticales premotoras-parietales similares pero, mientras que la IM reclutó una red subcortical similar a la de encontrada durante la ejecución real del movimiento, el entrenamiento de OA no mostró actividad en ninguna zona subcortical contradiciendo de esta manera algunos de los hallazgos encontrados por Munzert et al. (2008).

1.1.2 Modalidades de los métodos de representación de movimiento

Tanto el entrenamiento de OA, como el proceso de generación de IM pueden llevarse a cabo en distintas modalidades. Ambos métodos de representación de movimiento comparten que pueden ser implementadas en dos perspectivas. En primer lugar, existe la perspectiva en primera persona, donde la persona se observa o se imagina a sí misma mostrando su propio punto de vista. Por otro lado, se ha descrito una perspectiva en tercera persona, donde la persona se observa o se imagina a sí misma desde fuera, a modo de observador externo. Ambas formas han sido descritas y estudiadas en la literatura científica (Brady et al., 2011; Calmels et al., 2006; Ge et al., 2018; Montuori et al., 2018; Schuster et al., 2011; Vingerhoets et al., 2012; Wright & Smith, 2009).

En adición a la perspectiva en primera o en tercera persona, también denominada interna o externa, en la IM existe específicamente una subclasificación en dos modalidades más. En primer lugar, la IM denominada visual y en segundo lugar, la llamada IM cinestésica (Filgueiras et al., 2017; Mount, 1987). El cuestionario validado al Español de imagen del movimiento, conocido de manera abreviada como el cuestionario MIQ-R, contempla ambas modalidades y duplica los cuatro gestos motores funcionales analizados para poder evaluar las dos subescalas del cuestionario, la subescala visual y la subescala cinestésica, así como la total, obteniéndose mediante la sumación de las puntuaciones de ambas subescalas (Campos & Gonzalez, 2010).

A nivel teórico, las diferencias entre estas dos modalidades de construcción y generación de imágenes de movimiento residen en su ejecución. Por un lado, en la IM cinestésica se incorpora la capacidad de sentir a la vez que se lleva a cabo la tarea de generación de imágenes motoras provocando, a nivel neurofisiológico, algunas diferencias con respecto a la IM visual (Solodkin et al., 2004). Por ejemplo, durante la

IM cinestésica acontece un aumento de la actividad electromiográfica mayor que en la modalidad visual (Fadiga et al., 1998). Estos hallazgos también se encontraron en la estimulación del sistema corticoespinal evaluado a través de neuroimagen (Hashimoto & Rothwell, 1999). Incluso a nivel de la actividad del sistema neurovegetativo, también se ha encontrado que la modalidad cinestésica provoca mayores niveles de frecuencia cardíaca, respiratoria, conductancia de la piel, etc. (Decety et al., 1991; Oishi et al., 2000). La IM visual hace referencia exclusivamente a crear una imagen motora siendo, por tanto, una representación careciente de cualquier estimulación del sistema somatosensorial (Filgueiras et al., 2017; Solodkin et al., 2004) **(Figura 1)**.

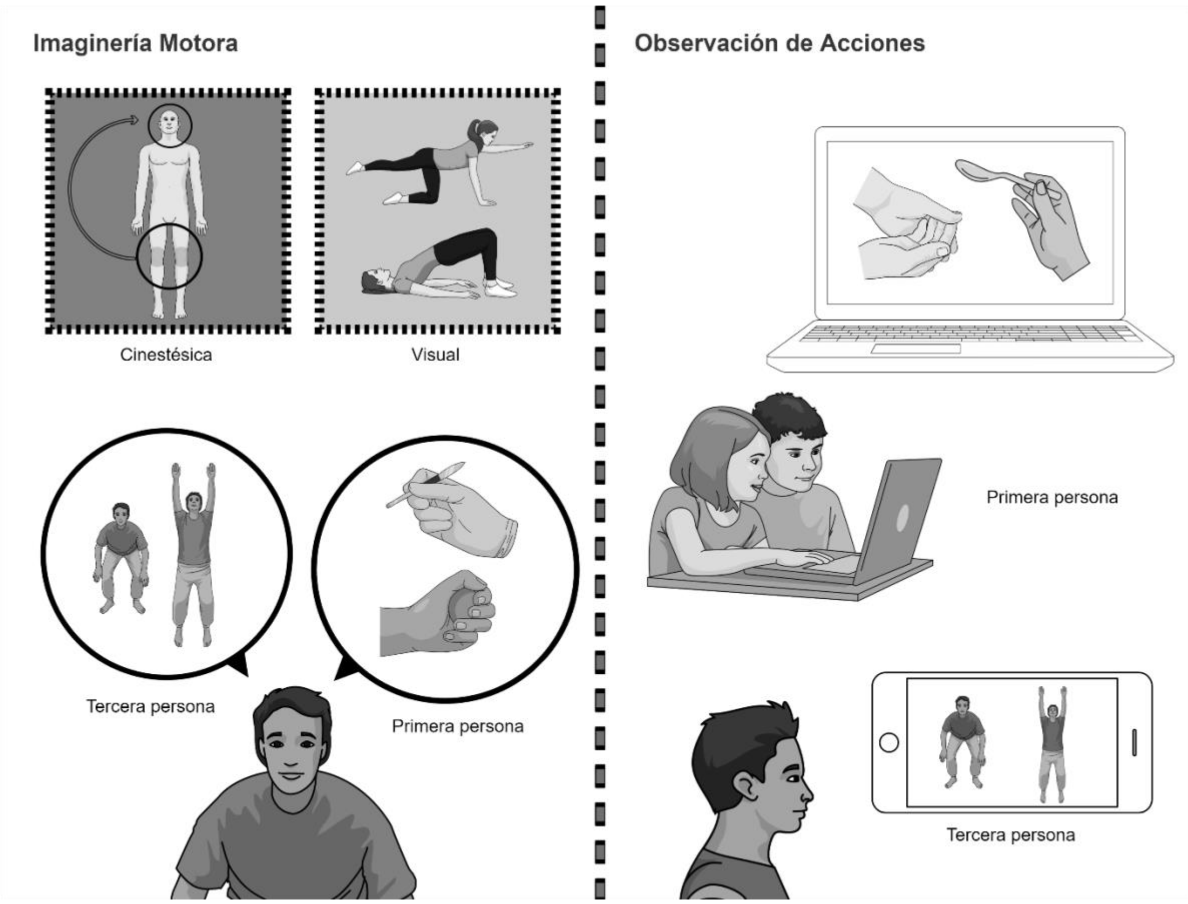

Figura 1. *Representación gráfica de las modalidades de la IM, así como del entrenamiento de OA*

El estudio conducido por Callow et al. (2013) muestra que cada modalidad de generación de imágenes motoras tiene unos beneficios en algunos contextos en comparación a otros. Por ejemplo, la IM visual y en perspectiva en tercera persona parece mostrar más efectividad que la IM visual y en perspectiva en primera persona en gestos motores que dependen ampliamente del conocimiento completo y generalizado del propio acto, casi de manera automatizada, para llevarse a cabo de manera correcta tales como el acto del dibujo, gestos de gimnasia o el deporte del kárate.

Sin embargo, la IM en perspectiva en primera persona y de manera visual ha mostrado efectos superiores en las tareas motoras donde la información de tipo perceptiva es de alta necesidad para la realización del gesto motor en cuestión, como el regate en el fútbol o para llevar a cabo un saque efectivo de tenis a alta velocidad, en comparación a la generación de IM en tercera persona y de manera visual (Callow et al., 2013).

Por otro lado, con respecto a la IM de tipo cinestésica, se ha sugerido que su mayor efecto se consigue sobre el aprendizaje de gestos motores que requieren de la acción coordinada y en connivencia de dos o más segmentos del cuerpo aunque previamente, se precisa de una característica fundamental: la experiencia previa sobre las propias tareas motoras para poder nutrir de información sensoriomotora a la corteza cerebral debido a que los gestos multisegmentales precisan de una alta carga de interacción somatosensorial (Callow et al., 2013). De hecho, en la comparación directa entre IM cinestésica y visual, recientemente Paris-Alemany et al. (2019) hallaron que en bailarinas y bailarines de ballet, estilo contemporáneo y flamenco, ante movimientos complejos y no familiares, estos utilizaban de manera más predominante una estrategia visual en la construcción y representación de imágenes de movimiento, necesitando además, de un mayor tiempo para realizar esta última. En adición a esto, en la comparación directa con sujetos sedentarios, los bailarines y bailarinas mostraron una mayor capacidad para representar imágenes motoras y además, necesitaron un menor tiempo para llevar a cabo dicha construcción de imágenes motoras mostrando así la importancia de la experiencia previa y de los niveles de actividad física en el proceso de representación de movimiento (Paris-Alemany et al., 2019a, 2019b).

Por otro lado, es importante enfatizar que la representación de imágenes de movimiento muestra algunas particularidades en el campo clínico, en concreto, en el dolor crónico. Recientemente, La Touche et al. (2018) encontraron que la capacidad de generar imágenes motoras, tanto de manera visual, como de una forma cinestésica, se encuentra reducida en los pacientes con dolor lumbar crónico no específico en comparación con sujetos sanos. Además, algunas variables han mostrado influenciar de manera significativa la representación de imágenes de movimiento. Por ejemplo, La Touche et al. (2018) también encontraron asociaciones positivas-moderadas entre mayor capacidad de generar imágenes motoras y mayores niveles de autoeficacia, así como asociaciones negativas-moderadas con respecto a mayores niveles de discapacidad y miedo al movimiento y una menor capacidad de representar y construir imágenes de movimiento en pacientes con dolor lumbar crónico no específico.

Teniendo en cuenta que en estos pacientes, la presencia de mayores niveles de autoeficacia determinan una mayor presencia de estrategias de afrontamiento activo, una mejor condición física, así como unos mayores niveles de actividad física, una menor presencia de aberraciones somatosensoriales y finalmente, un mayor rango de movimiento activo (Duray et al., 2018), parece que es crítica la condición física, así como los niveles de actividad física, modulados e influenciados por la esfera psicológica, en la construcción de imágenes motoras sobre todo, en pacientes con presencia de dolor mantenido en el tiempo, disfuncional y con carácter desadaptativo.

1.1.3 Influencia sobre variables físicas

Los métodos de representación de movimiento han sido estudiados ampliamente en relación a su influencia sobre variables físicas, tales como el rango de movimiento, la fuerza, la actividad electromiográfica, el equilibrio y el sistema de control postural, los niveles subjetivos de fatiga percibida, etc. (Frenkel et al., 2014; La Touche et al., 2019; Losana-Ferrer et al., 2018; Rozand et al., 2014).

Frenkel et al. (2014) encontraron que la IM combinada, visual y cinestésica, mostró buenos resultados en el mantenimiento del rango de movilidad de la mano tras una inmovilización prolongada y programada en sujetos asintomáticos. Argumentaron que los efectos beneficiosos de los métodos de representación de movimiento durante la inmovilización fueron, quizá, debidos a la propia representación de los movimientos de la mano y, por tanto, de la estimulación de las áreas cerebrales relacionadas con la generación y planificación del movimiento voluntario. En adición a esto, con respecto a las variables fuerza y actividad electromiográfica, Losana-Ferrer et al. (2018) encontraron que ambos métodos de representación de movimiento, en combinación con la práctica real, provocaron unos niveles de fuerza, así como una actividad electromiográfica mayor que la práctica física de manera aislada. Este aumento de la fuerza también se ha encontrado cuando se ha combinado el entrenamiento de OA y de IM de manera aislada, sin presencia de práctica real (Scott et al., 2017). Una de las teorías propuestas que podría justificar estos hallazgos anteriormente descritos es la teoría Psiconeuromuscular de Jacobson (1930). Esta, propone que durante la representación de un movimiento, en el sistema nervioso central se producen estimulaciones neurofisiológicas hacia los efectores musculares implicados en el gesto motor en cuestión, cualitativamente similar a las que acontecen cuando la acción se ejecuta de manera real, pero cuantitativamente menores en comparación a estas

(Sánchez & Lejeune, 1999). De hecho, la propuesta denominada *visuo-motor behavior rehearsal* está basada en esta teoría y fue Suinn (1985), Suinn (1972), quien encontró que la actividad electromiográfica era fundamentalmente equivalente en la musculatura elegida para la tarea motora en la comparación representación de un movimiento-práctica real.

Con respecto al equilibrio y al sistema de control postural, recientemente Marusic et al. (2018), encontraron que la combinación de IM, junto con el entrenamiento de OA en adición a un programa de tratamiento convencional, provocaron mejoras en tareas duales durante la marcha y sobre el control dinámico postural en comparación con el grupo sin someterse a la construcción de imágenes motoras en pacientes sometidos a cirugía de remplazo total de la articulación coxofemoral.

Finalmente, en relación a los procesos de aprendizaje, los métodos de representación de movimiento han mostrado tener un impacto significativo en el aprendizaje o re-aprendizaje de tareas motoras tanto en población asintomática (Cuenca-Martínez et al., 2019), como en población clínica (La Touche et al., 2019), mostrando este último además que la IM fue superior a otras potenciales estrategias de aprendizaje motor como la administración del *feedback* táctil, junto a la práctica real, específicamente en tareas de control sensoriomotor en pacientes con dolor lumbar crónico. Sin embargo, es necesario, en primer lugar, profundizar en el estudio del aprendizaje motor para posteriormente poder evaluar el actual estado del arte con respecto a los métodos de representación de movimiento y su influencia y relación con el mismo.

1.2 El Aprendizaje Motor

1.2.1 Concepto y marco teórico

El aprendizaje motor es una de las principales capacidades del ser humano siendo este definido como un conjunto de procesos asociados a la experiencia, y a la práctica derivada de la misma, que conducen a cambios relativamente permanentes y estables en las capacidades de respuesta (Riera, 1989). Existen una gran variabilidad de habilidades, movimientos, gestos o acciones motoras que pueden ser aprendidos a diario con un sentido adaptativo, es decir, en un intento de economización del esfuerzo y de los recursos energéticos, cognitivos y sensoriomotores (Huang et al., 2012; Sparrow & Newell, 1998).

Para que se pueda llevar a cabo el proceso de aprendizaje motor, existe un complejo sistema neurofisiológico perfectamente acoplado que interactúa consigo mismo y con el entorno (Wolpert et al., 2011). En primer lugar, procesos como la recolección o extracción de la información aferente sensoriomotora en la connivencia persona-ambiente, el procesamiento de dicha información con el objetivo de establecer algunos parámetros básicos de movimiento tales como la velocidad, la dirección, la intensidad o la fuerza, la aplicación de una serie de estrategias en la toma de decisiones, así como la salida de la señal eferente motora incluyendo una activación de procesos de control reactivo, biomecánico y de *feed-forward*, son algunos aspectos fundamentales en el proceso de aprendizaje y/o perfeccionamiento de nuevas tareas motoras (Wolpert et al., 2011). El control por *feed-forward,* es definido como un sistema anticipatorio de las situaciones que pueden ocurrir preparando estructuras corporales para poder hacer frente a los posibles disturbios contextuales de manera adelantada antes del inicio del movimiento (Seidler et al., 2004).

Este modelo neurofisiológico, anteriormente descrito, muestra profundas influencias de algunos modelos explicativos del aprendizaje motor tales como el modelo cibernético, o el modelo de procesamiento de la información, ambos, de corte predominantemente cognitivo tras el abandono de los modelos respondientes debido a la revolución cognitiva y al desarrollo de las teorías de la computación a partir de la segunda mitad del siglo XX (Boone & Piccinini, 2016; Famose, 1992; Greenwood, 1999; Miller, 2003). En adición a esto, el proceso de aprendizaje motor está ampliamente influenciado por una serie de variables tales como las recompensas o los errores (Palidis et al., 2018), así como la fuerte influencia de procesos cognitivos básicos tales como la memoria, la percepción o la atención (Famose, 1992).

1.2.2 Teorías y modelos interpretativos del aprendizaje motor

1.2.2.1 Teoría del circuito cerrado de Jack A. Adams

Algunas teorías que tuvieron el objetivo principal de ofrecer una explicación al proceso de aprendizaje motor, han sido descritas en la literatura científica. En primer lugar, la teoría del aprendizaje motor de Adams (1971), dentro del modelo cibernético, profería que durante el proceso de planificación y ejecución del movimiento voluntario, la señal corticoespinal eferente motora desencadenaba una acción en los efectores musculares provocando un resultado motor cualquiera. El conjunto de resultados generaría una experiencia, creando un cuerpo de conocimiento interno en base a la información proporcionada siendo esta creación de tipo continuo y siguiendo un circuito cerrado. Se distinguen dos etapas en el proceso de aprendizaje motor: la etapa verbal, caracterizada por el procesamiento de la información de forma consciente, y la etapa motora, donde aparece un sistema de control debido a la práctica y, por tanto, mediado por automatismos.

Con relación a la experiencia, esta provocaría un desarrollo de una memoria motora, denominada por Adams como huella de memoria, definida como la imagen de la representación del gesto motor. Por otro lado, se encontraría la huella perceptiva, definida como toda información sobre la acción del gesto motor. Ambas, influenciarían el sistema de control sensoriomotor para el perfeccionamiento de los siguientes gestos motores adaptando su ejecución a la imagen modelo, todo ello en coalición con un sistema de corrección cerrado, vía feedback, a través de información propioceptiva y exteroceptiva. La principal crítica a esta teoría fue dirigida hacia la aceptación de que existiese un número indeterminado de esquemas de movimiento específicos para cada uno de los gestos motores dados (Schmidt, 1975; Schmidt & Lee, 2013).

1.2.2.2 Teoría del esquema motor de Richard A. Schmidt

Schmidt (1975), acopló la teoría de Adams (1971) junto a la teoría de Keele (1973), a través de su teoría del esquema motor, argumentando que en lugar de haber infinitos programas motores para cada uno de los gestos motores voluntarios, existía un modelo de programación motora más general.

El esquema motor general, fijaría y establecería el programa motor global. Este hecho provocaría que se pudieran desarrollar diferentes patrones motores específicos o secundarios perfeccionados a través del aprendizaje. El esquema motor general inicial parte de información inicial propioceptiva y exteroceptiva (visual, vestibular y/o auditiva) (Schmidt, 1975). Las especificaciones de las respuestas motoras de los efectores musculares o del esquema motor, hacen referencia a las posibles divergencias de los patrones motores básicos debido a los cambios en distintos parámetros fundamentales tales como la fuerza, la intensidad o la velocidad.

Todo acto motor, provocaría secundariamente una consecuencia somatosensorial que serviría, a modo de *feedback*, para informar al sistema nervioso central en todo momento. Finalmente, se encontraría la información relativa al éxito de la respuesta, la cual se relaciona profundamente con el resultado esperado recibido probablemente a través de un *feedback* informacional externo. Es por tanto que el esquema motor, no es el programa motor general, sino que es un elemento necesario para que este pueda terminar convertido en una respuesta adaptada a una situación cualquiera.

Finalmente, en relación con la memoria, esta se establece mediante dos modelos de esquema: primero, el esquema elicitador, responsable de establecer relaciones informacionales del pasado junto con las actuales y, en segundo lugar, los esquemas de reconocimiento, encargados de la evaluación del propio gesto motor con una función de confrontación con la condición inicial, la experiencia y los propios resultados anteriores. Es por lo tanto que los mecanismos de control y aprendizaje motor estarían basados en la necesidad de creación y posterior consolidación de diversas representaciones centrales de los gestos motores a modo de esquemas motores (Schmidt, 1975).

Sin embargo, existen otras teorías, como las incluidas en la categoría de propuestas adaptativas, que difieren significativamente con las teorías del modelo cibernético o de las teorías del procesamiento de la información. Estas se encuentra basadas en distintos conceptos de la Psicología Ecológica y de la Teoría General de Sistemas Dinámicos (TGSD) (Newell, 2003; Sherwood & Lee, 2003; Ulrich & Reeve, 2005).

1.2.2.3 Teorías adaptativas del aprendizaje motor

Siguiendo esta línea, Moreno & Ordoño (2009) argumentaron que la TGSD considera que las teorías basadas en alegorías de amplia influencia computacional o cibernética, no son suficientes para poder explicar el aprendizaje y control del movimiento voluntario. La TGSD entiende el proceso de aprendizaje motor como un complejo sistema activo y dinámico donde el movimiento, es capaz de llevarse a cabo debido a la presencia de patrones asentados de coordinación creados a partir de la experiencia siendo estos, continuamente ajustados mediante el sistema neuro-musculoesquelético en su relación perenne con el ambiente. Es por tanto que esta teoría pivota en torno a la proposición de considerar a la persona, en combinación con el entorno, como un sistema dinámico y activo. Este, es activo debido a que está lejos de estar en equilibro, ya que se producen continuamente intercambios energéticos, químicos, informacionales, etc. y es dinámico debido a la capacidad de adaptación y cambio de los seres humanos.

Es por lo tanto que en un contexto motor dado, ante la presencia de cualquier cambio ambiental en el mismo, los patrones de coordinación provocarían mecanismos de adaptación con el objetivo de disminuir dicho desequilibro ajustándose, de manera más eficiente, mediante la acumulación experiencial. Es por ello por lo que, en los seres humanos, ante la continua y repetitiva exposición a la citada situación de desequilibrio demandante, se generaría un continuo tejido de adaptaciones que solventarían dicha condición de manera dinámica y eficiente. Los patrones de coordinación motora subyacerían a las demandas situacionales pudiendo provocar un mantenimiento y mejora de estos en el tiempo (Brymer & Renshaw, 2010; Davids et al., 2005). Por tanto, la complejidad, la búsqueda de equilibrio y la generación de adaptaciones como fundamento del continuo proceso de aprendizaje son los pilares básicos de esta teoría.

1.2.2.4 El modelo descriptivo de Fitts & Posner

Finalmente, uno de los modelos clásicos y más aceptados que intenta explicar las fases del aprendizaje motor es el modelo descriptivo en tres etapas de Fitts & Posner (1967). Los autores argumentan que en el proceso de aprendizaje de nuevos gestos motores existen al menos tres etapas: la etapa cognoscitiva, la etapa de asociación y, finalmente, la etapa de automatización. La primera, está caracterizada por una alta demanda cognitiva, donde es necesario buscar estrategias con respecto a los parámetros de movimiento efectivos, así como crear un sistema de detección de errores, etc. A este punto, existen un conjunto de variables clave que van a condicionar el paso por esta etapa. Estas serían variables cognitivas como la comprensión del gesto a ejecutar, expectativas de la propia capacidad de realización o la percepción de dificultad, así como variables motivacionales como los deseos, las aspiraciones o el empeño en la tarea (Fitts & Posner, 1967).

En las dos fases siguientes, la nueva actividad motora se integra y se alcanza progresivamente, donde los movimientos van precisando de una menor demanda cognitiva hasta el punto de poder automatizarse, es decir, hasta el punto de poder compaginar el gesto motor con la realización de otras acciones a la vez debido a que el requerimiento cognitivo es mínimo (Tinazzi & Zanette, 1998).

1.2.3 Aspectos neurofisiológicos de la generación del movimiento voluntario y los procesos de aprendizaje motor

Es ampliamente importante analizar la planificación, generación, ajuste y automatización del movimiento voluntario para poder posteriormente analizar algunos aspectos relevantes del aprendizaje motor en los seres humanos a través de la representación de movimiento.

En primer lugar, la vía de comunicación fundamental en la generación de movimiento voluntario se compone de las regiones cerebrales encargadas de la planificación y preparación del movimiento voluntario, junto a la corteza cerebral responsable de generar la señal eferente corticoespinal, previamente elaborada y procesada en áreas motoras secundarias, a través de la médula espinal hasta llegar a los efectores musculares generando un gesto motor cualquiera (Heckman & Enoka, 2004). Por tanto, la señal corticoespinal está ampliamente influenciada por la actividad de diferentes áreas corticales tales como el área premotora, área motora suplementaria, corteza somatosensorial primaria y la información talámica (Heckman & Enoka, 2004). Sin embargo, esto contiene una desmedida complejidad.

La corteza cerebral recibe información procesada de actividad motora del tálamo y también, información sensitiva no procesada (Perea-Bartolomé & Ladera-Fernández, 2004). Es por lo tanto que la corteza precisa de la sensibilidad (propiocepción, posición articular, información visual, etc.). Este hecho singular de recepción informacional de la corteza somatosensorial primaria implica que la corteza motora utiliza, además de información sensitiva procesada, información sensitiva proveniente de las estructuras talámicas (Perea-Bartolomé & Ladera-Fernández, 2004).

Es por tanto que ante un déficit sensitivo, así como cualquier problema de entrada de la información como por ejemplo en presencia de dolor mantenido, disfuncional y desadaptativo, o el propio desuso prolongado, la construcción del movimiento probablemente va a estar alterada debido a la calidad de la información sensitiva (Hodges & Tucker, 2011; Kim et al., 2017; Uremović et al., 2007). Este asunto también ha sido reportado en la literatura científica en pacientes con alodinia e hiperalgesia debido a la presencia de información propioceptiva aberrante (Jensen & Finnerup, 2014). Es por tanto que el producto final de presentar una alterada información aferente sea, probablemente, una alteración posterior en el proceso de generación del movimiento voluntario.

La corteza premotora recibe la misma información sensitiva, proveniente de las estructuras talámicas, que la corteza motora primaria y por tanto, existe un circuito redundante, vía tálamo, dando un valor crítico a la información sensitiva en el proceso de generación del movimiento voluntario (Behrens et al., 2003; Chouinard & Paus, 2006). En adición a esto, la corteza premotora recibe información cerebelosa, sobre todo, información propioceptiva no consciente (Bostan et al., 2013; Tanaka et al., 2009). La selección del plan maestro locomotor se introduce en este punto.

El cerebelo participa ampliamente en el proceso de aprendizaje motor ayudando a definir qué secuencias automáticas van asociadas a qué gestos específicos, es decir, realiza una programación automática de los gestos motores elegidos para un determinado fin (golpear la pelota en un punto y en unos parámetros específicos, hacer un rápido y preciso saque de tenis, dar un gran salto para rematar un balón, etc.) (De Zeeuw & Ten Brinke, 2015; Thach, 1998). Todo esto funciona en modo automático y, por tanto, el programa motor está elegido, poniéndose en marcha una serie de automatismos para poder llevarse a cabo la acción dada. Estos automatismos son cerebelosos y funcionan en connivencia con el área premotora y el área motora suplementaria para ayudar a la selección del plan motor (Thach, 1998; VanMeter et al., 1995). Es por lo tanto que la función del cerebelo, así como su comunicación con las áreas motoras secundarias, parecen críticos en el aprendizaje motor.

Por otro lado, el lóbulo frontal también participa ampliamente en la generación, ajuste y aprendizaje motor debido a que sobre el área premotora, la cual influye posteriormente sobre el área motora primaria, existen influencias cognitivas y estas, están moduladas por los ganglios de la base (Exner et al., 2002; Jueptner et al., 1997; Ono et al., 2015).

Las bases relacionales se establecen en que las influencias cognitivas pueden modificar el plan maestro motor previamente generado por los mecanismos automáticos provenientes del cerebelo (Exner et al., 2002). Existe, por tanto, una toma de decisiones a través de la utilización de información no automatizada para modificar un engrana motor dado con algún tipo de fin voluntario específico (cambiar un pase en el último momento, cambiar la elección de un golpe en tenis, etc.). Estos cambios ejecutivos rápidos son ampliamente observables en deportistas de alto rendimiento donde se puede observar cómo estos procesos cognitivos acontecen alimentando a la corteza motora en fases críticas de la competición.

En adición a esto, otra región relacionada ampliamente en la generación y sobre todo ajuste de movimientos voluntarios, así como el aprendizaje motor es el lóbulo parietal, áreas 5 y 7 de Brodmann (Whitlock, 2017). Estas áreas están relacionadas con la asociación de estímulos sensitivos y donde además, participa también el proceso cognitivo básico de memoria (Pisella, 2017; Rutishauser et al., 2018).

En primer lugar, la corteza parietal posterior es un sistema de integración sensitiva y de memoria la cual, tiene una función de llevar a cabo una predicción natural (Blakemore & Sirigu, 2003; Whitlock, 2017). La principal contrariedad es que es un sistema de elevada necedad, el cual, si se pide una tarea específica cualquiera a ejecutar, a pesar de poder crearse un contexto óptimo a través de una alimentación de información sensitiva preponderante y rica (visual, propioceptiva, vestibular, etc.,) puede conducir a una predicción desacertada, es decir, puede utilizar información no real, y en modo automático, en lugar de una información efectiva (frecuencia cardíaca, frecuencia respiratoria, fatiga percibida, distancia, características del balón, peso, etc. a tiempo real), pudiendo dar lugar a algunos errores de predicción natural (Blakemore & Sirigu, 2003; Cui, 2016).

Continuando con los aspectos neurofisiológicos de la generación, ajuste y aprendizaje de gestos motores voluntarios, la corteza motora suplementaria recibe información del tálamo y este, contiene información procesada, información subcortical de los ganglios de la base e influencias cognitivas (Ferrández et al., 2003; Iansek et al., 1995). En los ganglios de la base es donde se llevan a cabo todos los circuitos de modulación, donde por tanto, el mensaje de la información eferente corticoespinal viaja por los ganglios de la base y estos, retroalimentan la corteza motora suplementaria para modular algunos parámetros como la intensidad, la frecuencia o permitiendo la participación de otras estructuras y circuitos (Iansek et al., 1995).

Los ganglios de la base se constituyen de cuatro asas o cuatro epígrafes fundamentales formados primero, por un asa motora, que es el sistema en el que se transmite la información corticoespinal y a su paso, estas estructuras retroalimentan diferentes características y parámetros inherentes al movimiento programado en el esquema motor (velocidad, fuerza, dirección, etc.) provocando que se seleccione una organización secuencial igual, o quizá diferente de la que se había seleccionado en un primer momento en función del contexto, a modo de sistema de ajuste en directo (Lanciego et al., 2012).

En segundo lugar, se encuentra el asa límbica, responsable de la participación de las emociones y, por tanto, del componente motivacional-afectivo en el contexto del movimiento voluntario. Por tanto, la vía corticoespinal tiene una relación neuro-anatómica con el sistema límbico, vía ganglios basales.

Tercero, está el asa oculomotora, la cual a través del reflejo vestíbulo-ocular es capaz también de modificar la actividad motora. Por último, el asa cognitiva, aprendizaje, ejecución automática, etc. Todo este complejo sistema anatómico funciona siguiendo una organización a modo de balanza o compensación entre el gasto de procesos cognitivos y el gasto de procesos automáticos buscando un equilibrio economizando el gasto energético y neuro-fisiológico (Groenewegen, 2003). Es por lo tanto que los ganglios basales van a influir de manera preponderante en el proceso de regulación del movimiento automático y del movimiento estrictamente voluntario. La **Figura 2** representa un pequeño esquema respecto a los aspectos neurofisiológicos de la generación del movimiento voluntario y el proceso de aprendizaje motor.

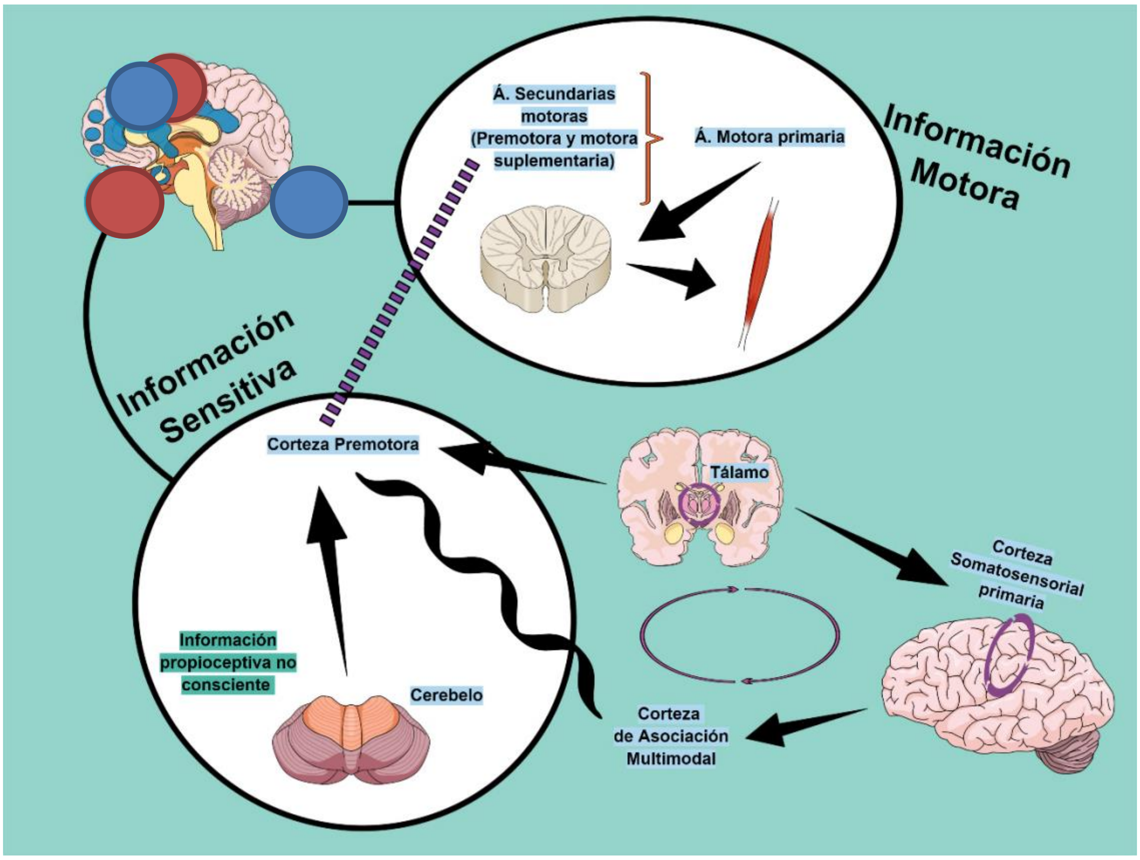

Figura 2. *Representación esquemática de parte de la neurofisiología del movimiento voluntario*

Finalmente, existe un sistema extrapiramidal el cual, está ampliamente relacionado con el ajuste del movimiento voluntario (de Oliveira-Souza, 2012; Bruggencate, 1975). El conjunto formado por la vía tectoespinal, rubroespinal, vestibuloespinal y reticuloespinal modula la actividad motora facilitando la aparición de algunos automatismos, facilitan la contracción de musculatura proximal, intervienen en el mantenimiento del equilibrio en gestos motores que involucran la cabeza y el cuello, etc., siendo estos sistemas automáticos y ampliamente importantes en la generación y sobre todo, ajuste del movimiento humano (de Oliveira-Souza, 2012).

1.3 Métodos de Representación de Movimiento Aplicado al Aprendizaje Motor

1.3.1 Marco teórico e investigaciones previas

Los métodos de representación de movimiento aplicados al aprendizaje motor han sido anteriormente estudiados en el campo de la neurociencia cognitiva y en la psicología del deporte (Frank et al., 2014; Higuchi et al., 2012; Ste-Marie et al., 2012; Vogt et al., 2007). Finke (1979), desarrolló la hipótesis de equivalencia funcional la cual proponía que el proceso de representación de movimientos comparte un cierto grado de actividad cerebral solapada con la que ocurre durante la ejecución motora real durante los procesos neurofisiológicos de preparación y planificación de un movimiento voluntario dado. Esto posteriormente ha sido comprobado mediante neuroimagen (Hétu et al., 2013; Munzert et al., 2009).

Tanto la IM como el entrenamiento de OA han sido utilizados tanto de forma separada (La Touche et al., 2019; Lacourse et al., 2005; Ste-Marie et al., 2012), como de forma combinada (Vogt et al., 2013) para evaluar su impacto sobre el proceso de adquisición de diversas habilidades motoras. Por ejemplo, la IM ha mostrado facilitar el aprendizaje motor en diversos contextos y campos del deporte como por ejemplo la devolución del servicio, llamado resto, en el tenis (Robin et al., 2007), en el golf (Bell et al., 2009), en distintas rutinas de trampolín (Isaac, 1992), en el mantenimiento de la estabilidad del tempo en el campo de la música (Johnson, 2011), en la danza (Abraham et al., 2016) e incluso en el aprendizaje y mejora de diferentes habilidades quirúrgicas (Arora et al., 2011). El entrenamiento de OA también ha mostrado facilitar el aprendizaje motor (Hayes et al., 2010; Heyes & Foster, 2002; Vinter & Perruchet, 2002).

En adición a esto, Gatti et al. (2013) y Doyon & Benali (2005), mostraron que existen habitualmente dos paradigmas ampliamente utilizados en el estudio de los mecanismos que conducen al aprendizaje motor de nuevas habilidades motoras: por un lado, el aprendizaje de una secuencia motora, donde se evalúa la adquisición del incremento de movimientos en una condición experimental dada, y en segundo lugar, el modelo de adaptación, el cual, se evalúa la capacidad de la compensación delante de los posibles cambios acontecidos o provocados en el ambiente. Para ambos paradigmas, distintas fases del aprendizaje pueden ser distinguidas. Una etapa rápida, donde la adquisición acontece dentro de una sola sesión de entrenamiento. Una etapa de consolidación, en la cual, una mejora de la realización ocurre hasta al menos las seis horas siguientes de la fase rápida. Una etapa lenta, donde el aprendizaje ocurre por la acumulación de práctica. Una etapa automática, donde la demanda cognitiva es baja y finalmente, una fase de retención, en la cual, la realización del gesto motor dado puede ser realizado en total ausencia de cualquier práctica posterior (Doyon & Benali, 2005; Gatti et al., 2013).

Es importante remarcar que el estudio conducido por Gatti et al. (2013), ofrece alguna respuesta también en torno a la descripción de los mecanismos neurofisiológicos subyacentes al proceso de aprendizaje motor. El estudio, habla de dos modelos; el modelo de Dayan & Cohen (2011), y el descrito por Doyon & Benali (2005).

El primero, argumenta que existen dos circuitos que operan en paralelo en el aprendizaje de las características espaciales y motoras presentes en las secuencias motoras. Por un lado, el aprendizaje de coordenadas espaciales estaría soportado por un circuito fronto-parietal asociativo estriado-cerebelar, mientras que el aprendizaje de las coordenadas motoras, lo estaría por un circuito sensoriomotor primario estriado-cerebelar (Dayan & Cohen, 2011). En ambos circuitos en paralelo, coexisten y cooperan estructuras corticales, subcorticales y el cerebelo.

Por otro lado, el segundo modelo propuso que, durante el aprendizaje rápido, hay una actividad del asa cortico-estriado-tálamo-cortical, y además, un asa cortico-cerebelo-tálamo-cortical, actuando ambos también en paralelo. Este modelo postula que la connivencia entre estos dos subsistemas, es un aspecto crítico para el establecimiento de las rutinas motoras necesarias para el aprendizaje o reaprendizaje de un gesto o habilidad motora (Gatti et al., 2013).

En adición, y pesar de esto, solamente un reducido y limitado número de estudios han comparado los efectos entre los métodos de representación de movimiento de manera aislada, con o sin la presencia de la práctica real en el proceso de aprendizaje motor. En relación a esto, aunque ambos métodos de representación de movimiento han mostrado tener una influencia significativa en el aprendizaje de algunos gestos motores, parece que los estudios han mostrado que el entrenamiento de OA es, tal vez, más efectivo que el entrenamiento de IM a corto plazo, inmediatamente tras finalizar una intervención (Gatti et al., 2013; González-Rosa et al., 2015; McCormick et al., 2013; Roosink & Zijdewind, 2010). Sin embargo, y a pesar de estos hallazgos, existen todavía una serie de incógnitas que necesitan una respuesta en este proceso de evaluación y análisis comparativo.

1.3.2 Uso de los métodos de representación de movimiento en el reaprendizaje y reacondicionamiento motor tras el desuso

Los métodos de representación de movimiento no solamente parece que tienen la capacidad de favorecer la adquisición de nuevos gestos motores o el aprendizaje de una secuencia desconocida de gestos aprendidos, sino también parece que pueden tener un impacto en el reaprendizaje motor así como en la prevención y minimización del impacto del desuso. Existen algunos estudios que han mostrado que la inclusión de IM y

OA a un programa habitual de intervención es capaz de conducir a un reaprendizaje motor, así como una mejora de distintas variables sensoriomotoras como la fuerza, equilibrio o el estado funcional de manera significativamente superior a la no inclusión de estos métodos de representación de movimiento en pacientes postquirúrgicos (Bellelli et al., 2010; Cupal & Brewer, 2001; Id et al., 2019; Moukarzel et al., 2019; Park et al., 2014; Villafañe et al., 2016, 2017). Datos similares han sido encontrado en sujetos sanos que han sido inmovilizados experimentalmente (Clark et al., 2014; Frenkel et al., 2014; Newsom et al., 2003).

El desuso mantenido, bien debido a una lesión con o sin cirugía, o bien provocado experimentalmente en sujetos sanos, parece que conduce hacia cambios neurobiológicos y neuroplásticos desadaptativos a nivel central, así como en la función motora a nivel periférico (Campbell et al., 2019; Langer et al., 2012). A nivel cortical, Langer et al., (2012) encontraron que tras dos semanas de inmovilización, la corteza motora primaria responsable del miembro reducía su volumen y además, la sustancia blanca de la vía corticoespinal dependiente de la corteza motora primaria también disminuía. Es por tanto que el desuso parece que puede provocar un proceso neurofisiológico de depresión cortical y esta podría ser la diana de los métodos de representación de movimiento. La hipótesis, elaborada por Sale y por Eonka & Fuglevand (Christakou et al., 2007; Sale, 1988), denominada como la hipótesis del entrenamiento neural, profiere que los cambios a nivel central son los responsables y causantes de un cambio en la actividad sensoriomotora periférica. Esta hipótesis fue posteriormente apoyada por algunos trabajos. Por ejemplo, Jowdy & Harris (2016) encontraron un aumento significativo de la actividad muscular durante la aplicación de métodos de representación de movimientos, evaluado a través de la electromiografía de superficie. En adición a esto, la construcción de imágenes de movimiento podría conducir a una mejor representación del proceso de generación de fuerza motora a nivel central, es decir, en las regiones corticales responsables de la programación y planificación central del sistema motor (Annett, 1995; Jeannerod, 1995). En base a toda esta argumentación, parece que los métodos de representación de movimiento podrían tener un impacto a nivel central y, por consiguiente, a nivel periférico.

JUSTIFICACIÓN

2. Justificación del Trabajo Realizado

El aprendizaje motor es un campo fundamental en distintas áreas de interés, tales como la rehabilitación neurológica (Krakauer, 2006; Maier et al., 2019), traumatológica (Masters et al., 2008; Opie et al., 2016), el deporte (Annett, 1994; Fuelscher et al., 2012), la música (Palmer & Meyer, 2000; Sidnell, 1986), e incluso la comunicación y el lenguaje (Iverson, 2010; Shiller et al., 2010).

Algunas investigaciones previas han mostrado que ambos métodos de representación de movimiento tienen un impacto sobre el proceso de aprendizaje motor tanto de manera aislada (Frenkel et al., 2014), como en combinación con otras intervenciones (Allami et al., 2008). Además, estos hallazgos han sido encontrados en población asintomática (Dana & Gozalzadeh, 2017; Lebon et al., 2010; Robin et al., 2007), pero también en población clínica (La Touche et al., 2019; Villafañe et al., 2016).

A pesar del número elevado de trabajos que se han reportado en la literatura científica con respecto a la influencia de los métodos de representación de movimiento sobre el proceso de aprendizaje motor, son todavía escasos los artículos que analizan no solamente la efectividad, sino también la comparación de estos entre las distintas técnicas que conforman los métodos de representación de movimiento. Los resultados de un número reducido de investigaciones anteriores en esta línea han mostrado que el entrenamiento de OA parece provocar un mayor aprendizaje motor de gestos complejos, a través de un análisis cinemático, en comparación con la IM solamente a muy corto plazo (Gatti et al., 2013; González-Rosa et al., 2015).

Aun así, y a pesar de esto, consideramos que todavía es necesario contar con un mayor número de estudios que ofrezcan soporte a estos hallazgos, teniendo en cuenta la importancia del seguimiento para evaluar cualquier proceso de aprendizaje y además, que evalúen el efecto de los métodos de representación de movimiento sobre el aprendizaje motor tanto en combinación con la práctica real, como con ausencia de la misma. En adición a esto, creemos también que es importante realizar estudios con población clínica, y no solamente asintomática, para poder dar respuesta a algunas preguntas a nivel clínico y no solamente abordar estas a través de una evidencia indirecta, es decir, a partir de inferencias derivadas de estudios con población no clínica, o subclínica. Finalmente, creemos también que una profunda revisión de la literatura científica es necesaria con respecto al papel de los métodos de representación de movimiento en el desuso mantenido bien por lesión con o sin cirugía, así como en sujetos asintomáticos sometidos a una inmovilización experimental.

Es por tanto que, debido al número limitado de estudios que versan sobre una evaluación y un análisis comparativo entre métodos de representación de movimiento sobre el aprendizaje motor, junto con la ausencia de seguimiento en los estudios subyacentes al actual estado del arte, así como de la falta de estudios en población clínica, y la difusa separación entre estudios que combinan los métodos de representación de movimiento con, o por el contrario sin, la práctica real, creemos que es importante plantear un conjunto de investigaciones que involucren a la región lumbar, a la región cervical y finalmente los miembros superiores, en concreto, las manos por su funcionalidad, para poder dar respuesta a si ambos métodos de representación de movimiento tienen un impacto en el aprendizaje motor en diferentes tipos de gestos motores y en distintas regiones corporales, y si además, una técnica tiene un efecto mayor a la otra o por el contrario no, y si es así, hasta cuanto tiempo, en qué población, en qué región corporal o en qué tipo gesto motor acontece.

Estos son los motivos centrales que justifican la presente tesis doctoral. La evidencia científica más actual nos ha llevado a la reflexión sobre las limitaciones que existen con relación a los métodos de representación de movimiento sobre el aprendizaje motor, siendo difícil dar respuesta a algunas incógnitas debido a las constantes pendencias entre la funcionalidad y la construcción teórica. A través de esta tesis doctoral, hemos intentado dar respuestas a diversos interrogantes desde un punto de vista funcional, pero también desde un punto de vista estrictamente teórico, incluyendo, además, regiones corporales donde la presencia de dolor persistente es altamente común, gestos motores ampliamente utilizados en la práctica clínica, un seguimiento hasta el corto/medio plazo y finalmente, distintas poblaciones incluyendo población clínica.

HIPÓTESIS

3. Planteamiento de las Hipótesis

En primer lugar creemos que ambos métodos de representación de movimiento, la IM y el entrenamiento de OA, van a conducir a un proceso de aprendizaje motor relativamente estable en el tiempo con y sin la adición de un entrenamiento real. Esta hipótesis de corte más general se encuentra apoyada en algunos hallazgos encontrados en investigaciones previas como las encontradas por Allami et al. (2008), La Touche et al. (2019) o Yágüez et al. (1998) entre otros, y también, en base a algunas construcciones teóricas como las propuestas por Mattar & Gribble (2005) o Guillot & Collet (2005).

Sin embargo, también creemos que el entrenamiento de OA va a conducir a un aprendizaje motor mayor que la IM en sujetos asintomáticos debido a la propia neurofisiología que subyace a los métodos de representación de movimiento descritos por Buccino (2014). Esta hipótesis estaría basada en los hallazgos encontrados previamente por Gatti et al. (2013) y por González-Rosa et al. (2015). La investigación llevada a cabo con seguimiento nos va a permitir dar mayor soporte a estos hallazgos previos y no solamente eso, sino además durante cuánto tiempo podría esto ocurrir hasta un total de 4 meses de seguimiento que tiene como duración la investigación. Hasta el momento no hemos encontrado ningún artículo que evalúe el proceso de aprendizaje motor a través de los métodos de representación de movimiento con tanto tiempo de seguimiento.

En adición a esto, también vamos a tener información clínica debido a que sobre pacientes con dolor de cuello crónico vamos a poder evaluar cuál de los métodos de representación de movimiento provoca un efecto mayor en el proceso de aprendizaje motor de movimientos activos fisiológicos del cuello. Investigaciones previas, como las llevadas a cabo por La Touche et al. (2018) o Pérez-Fernández et al. (2015), han encontrado que el entrenamiento de OA puede evocar situaciones aversivas como el miedo o incluso pueden evocar dolor en pacientes con dolor crónico. En base a estos hallazgos, creemos que el entrenamiento de OA no será más efectivo que la IM en las primeras fases de aprendizaje motor de movimientos activos cervicales.

Además, los autores también hipotetizan que no va a haber diferencias entre los métodos de representación de movimiento cuando estos se apliquen en combinación con el ejercicio real. Es probable que estas diferencias se minimicen cuando se manifiesten las mejorías debidas al ejercicio activo real tal y como encontraron previamente Losana-Ferrer et al. (2018) sobre la mejora de distintas variables físicas.

Además, creemos que los métodos de representación de movimiento van a tener un impacto en el proceso de reaprendizaje motor así como en la minimización del impacto del desuso en pacientes con lesión, sometidos o no a cirugía, así como en personas sanas sometidas a una inmovilización experimental. Para dar respuesta a esta hipótesis final, se requerirá de una realización de una revisión sistemática con meta-análisis para evaluar el actual estado del arte con respecto a los métodos de representación de movimiento sobre variables sensoriomotoras tanto en pacientes como en sujetos sanos sometidos a un periodo relativamente mantenido de desuso. Creemos que la aplicación tanto de la IM, como del entrenamiento de OA, van a preservar un mayor rango de movilidad, una mayor fuerza así como un mejor estado de distintas variables sensoriomotoras en comparación con la no utilización de estos métodos en base a distintas conceptualizaciones teóricas propuestas por algunos autores como Hale (2016), Christakou & Zervas (2007) o Ranganathan et al. (2004).

Finalmente, creemos que el proceso neurofisiológico de construcción de imágenes motoras difiere durante la aplicación de IM y durante el entrenamiento de OA. Para ello se realiza un estudio de hipótesis con revisión. Los autores hipotetizan que existiría un total de cuatro dominios donde podrían clasificarse el conjunto de variables que podrían modular el efecto de la representación de movimiento. Estos dominios serían: a) dominio físico, b) dominio cognitivo-evaluador, c) dominio motivacional-afectivo, y finalmente d) dominio de modulación directa sobre la representación motora. Dentro de los métodos de representación de movimiento, la IM quizá sea la herramienta más susceptible a la influencia de estas, debido a las características inherentes al proceso de creación de imágenes mentales motoras.

La activación neurofisiológica cortico-subcortical que ocurre durante la representación de un movimiento, es probable que elicite la formación de una huella mnémica específica y duradera de las representaciones de los movimientos en las fases del aprendizaje motor. Los autores hipotetizan un conjunto de argumentos con relación a la creación de la memoria motora y al proceso de integración de la información visual:

Primero, creemos que el camino neurofisiológico que siguen ambos métodos de representación de movimiento en el proceso de adquisición e integración de la información visual es diferente. Por tanto, van a existir diferentes estrategias en el proceso de creación de la huella motora.

Segundo, la construcción de la imagen a través de la IM probablemente sea alimentada en primer lugar, por la actividad continua de la memoria operativa y, en segundo lugar y a través de la actividad del relé episódico, reciba también información de la memoria episódica. Por tanto, la IM requiere necesariamente de estrategias conscientes en el proceso de creación de la imagen y, por tanto, de una alta carga cognitiva. Esto podría explicar la fatiga que experimentan los sujetos durante el proceso de construcción de la imagen a través de la IM.

Tercero, pensamos también que el entrenamiento de OA no es necesariamente dependiente del uso de estrategias conscientes debido a la eficiencia que supone que la imagen sea ofrecida de manera externa, con lo que predominantemente hay que retenerla y comprenderla en lugar de crearla, facilitando así el trabajo de la memoria operativa y facilitando, por tanto, la construcción de la huella motora. Por tanto, existe obligatoriamente una transformación de la imagen y puede haber un trabajo consciente durante el entrenamiento de OA pero probablemente requiera de una menor carga de trabajo en comparación con la que se precisa con la IM.

Cuarto, esta actividad neurofisiológica optimizada entre el control ejecutivo central, el cual pertenece a la memoria operativa, y la memoria procedimental es probable que permita la adquisición de estrategias sin ser conscientes de las regularidades que gobiernan el propio proceso de adquisición de las mismas. Es por lo tanto que es probable que, en el proceso de creación de la huella motora a través del entrenamiento de OA, haya una mayor implicación de un aprendizaje de tipo implícito bajo la participación de la memoria procedimental perceptivo-motora.

Finalmente, esto podría también dar respuesta a las diferencias que existen en la susceptibilidad sobre la influencia de variables físicas, cognitivas, motivacionales-afectivas y de modulación directa entre ambos métodos de representación de movimiento, mostrando una mayor robustez a la influencia el entrenamiento de OA.

OBJETIVOS

4. Objetivos

El objetivo general de la presente investigación que conforma esta tesis doctoral fue evaluar y comparar los efectos de los métodos de representación de movimiento, a través de la observación de acciones y de la imaginería motora, en el aprendizaje motor tanto en sujetos asintomáticos como en población clínica.

A continuación, se detallan los objetivos específicos:

1-. Evaluar y comparar los efectos del entrenamiento de observación de acciones e imaginería motora, en combinación con la práctica real, sobre tareas de control sensoriomotor lumbo-pélvico en sujetos asintomáticos.

Este objetivo se ha abordado en la siguiente publicación original:

- **Cuenca-Martínez F**, Suso-Martí L, Sánchez-Martín D, Soria-Soria C, Serrano-Santos J, Paris-Alemany A, La Touche R, & León-Hernández JV. Effects of motor imagery and action observation on lumbo-pelvic motor control, trunk muscles strength and level of perceived fatigue: a randomized controlled trial, *Research Quarterly for Exercise and Sport*. 2019;91(1):34-46. DOI: 10.1080/02701367.2019.1645941

2-. Evaluar y comparar los efectos de los métodos de representación de movimiento a través del entrenamiento de observación de acciones e imaginería motora, de manera aislada, sobre el aprendizaje motor en pacientes con dolor de cuello crónico no específico a corto plazo.

Este objetivo se ha abordado a través de la siguiente publicación original:

- **Cuenca-Martínez F**, La Touche R, León-Hernández JV, & Suso-Martí L. Mental practice in isolation improves cervical joint position sense in patients with chronic neck pain: A randomized single-blind placebo trial, *PeerJ*. 2019;7:e7681. DOI: 10.7717/peerj.7681

3-. Evaluar y comparar a corto/medio plazo el efecto de los métodos de representación de movimiento, a través del entrenamiento de observación de acciones e imaginería motora, de manera aislada, sobre el aprendizaje motor de una secuencia de posiciones manuales motoras, de complejidad creciente, en sujetos asintomáticos.

Este objetivo ha sido abordado a través de la siguiente publicación original:

- **Cuenca-Martínez F**, Suso-Martí L, León-Hernández JV, & La Touche R. Effects of movement representation techniques on motor learning of thumb-opposition tasks, *Scientific Reports*. 2020. DOI: 10.1038/s41598-020-67905-7

4-. Llevar a cabo una revisión narrativa, así como el planteamiento de una hipótesis neurofisiológica, con perspectiva bioconductual, sobre el análisis y la evaluación de los métodos de representación de movimiento en el proceso de aprendizaje motor, incluyendo las diferencias en el proceso de generación de la imagen de movimiento entre los métodos de observación de acciones e imaginería motora.

Este objetivo ha sido abordado a través de la siguiente publicación original:

Cuenca-Martínez F, Suso-Martí L, León-Hernández JV, & La Touche R. The Role of Movement Representation Techniques in the Motor Learning Process: A Neurophysiological Hypothesis and a Narrative Review, *Brain Sciences*. 2020. DOI: 10.3390/brainsci10010027

5-. Evaluar el efecto de los métodos de representación de movimiento sobre las variables fuerza, rango de movilidad, velocidad de paso, estado funcional general y equilibrio durante los procesos de inmovilización experimental en sujetos sanos, en pacientes con lesiones que no requirieron cirugía y en pacientes postquirúrgicos que requirieron o no de un proceso de inmovilización.

Este objetivo ha sido abordado a través del siguiente estudio:

Cuenca-Martínez F, Angulo-Díaz-Parreño S, Feijóo-Rubio X, Fernández-Solís MM, León-Hernández JV, La Touche R & Suso-Martí L. Motor Effects of Movement Representation Techniques and Cross-Education Training in Recovery and Immobilization Processes: A Systematic Review and Meta-Analysis.

RESULTADOS

5. Resultados

Artículo 1

Effects of motor imagery and action observation on lumbo-pelvic motor control, trunk muscles strength and level of perceived fatigue: a randomized controlled trial.

"Efectos de la imaginería motora y el entrenamiento de observación de acciones en el control motor lumbo-pélvico, la fuerza de la musculatura del tronco y el nivel de fatiga percibida: un ensayo controlado aleatorizado."

Objetivo: El objetivo del presente estudio fue evaluar los efectos de la IM y del entrenamiento de OA combinadas con un programa de ejercicios de control sensoriomotor en la región lumbo-pélvica.

Métodos: Una muestra total de cuarenta y cinco sujetos asintomáticos fue distribuida de manera aleatoria en tres grupos: IM (n = 15), AO (n = 15) y grupo de control (CG) (n = 15). Las medidas de resultado incluyeron el control sensoriomotor lumbo-pélvico objetivado a través de un estabilizador de presión *biofeedback*, la fuerza muscular del tronco mediante un dinamómetro y la fatiga percibida a través de una escala analógica visual. Los participantes fueron evaluados antes de la intervención (pre-intervención), en la primera semana de intervención (evaluación intermedia) e inmediatamente tras finalizar las tres semanas de intervención (post-intervención).

Resultados: Con respecto al control sensoriomotor lumbo-pélvico, se observaron diferencias intragrupo estadísticamente significativas entre la evaluación inicial y la evaluación intermedia e inmediatamente posterior a la intervención en el grupo intervenido a través del entrenamiento de OA con un tamaño del efecto grande ($p <$

0,001; $d > 0,80$). Los grupos IM y GC mostraron diferencias dentro de cada grupo estadísticamente significativas solamente entre la evaluación pre-intervención e inmediatamente tras finalizar la intervención también con un tamaño del efecto grande ($p < 0,05$; $d > 0,80$).

En adición a esto, se llevó a cabo una comparación directa entre las diferencias de medias obtenidas entre la evaluación intermedia y la evaluación pre-intervención (ΔMed-Pre) con el objetivo de evaluar la velocidad de los efectos de las herramientas de representación de movimiento. Con respecto a la citada comparación directa ΔMed-Pre (ΔOA vs. ΔIM vs. ΔGC), solamente el grupo de OA fue superior al GC con un tamaño de efecto grande ($p = 0,03$; $d = 0,93$ en el control sensoriomotor lumbo-pélvico del miembro inferior izquierdo, y $p = 0,036$; $d = 0,94$ en el del miembro inferior derecho). Sin embargo, el grupo de OA no fue superior al grupo de IM ($p > 0,05$). Finalmente, el grupo de IM no fue significativamente más rápido que el GC ($p > 0,05$).

Con respecto a la fuerza de la musculatura del tronco, se observaron diferencias dentro de cada grupo estadísticamente significativas entre la evaluación pre-intervención y la evaluación post-intervención solamente en los grupos de combinación de práctica real con métodos de representación de movimiento ambas con un tamaño del efecto grande: OA ($p < 0,001$; $d = -1,25$) e IM ($p < 0,05$; $d = -1,00$). Sin embargo, no se hallaron diferencias entre ambos grupos de intervención ($p > 0,05$). No se encontraron diferencias estadísticamente significativas en el GC ($p > 0,05$).

En relación con la fatiga percibida, se encontraron diferencias dentro de cada grupo estadísticamente significativas en todos los grupos con un tamaño del efecto moderado-grande entre la evaluación pre-intervención y la evaluación intermedia ($p < 0,05$; $d >$

0,60) y con un tamaño del efecto grande entre la evaluación pre- y post-intervención (p < 0,001; *d* > 0,80).

Conclusiones: Los resultados del presente estudio mostraron que la inclusión de los métodos de representación de movimiento afectó significativamente al proceso de aprendizaje de gestos motores complejos tales como los ejercicios de control sensoriomotor. El uso de la OA, junto con la práctica real del gesto motor, condujo a un aprendizaje motor más rápido, variable que debería ser considerada en el aprendizaje de gestos motores complejos dentro de la práctica deportiva. Además, los ejercicios de control sensoriomotor son ampliamente implementados en el campo de la rehabilitación, ya que muestran resultados positivos en la reducción del dolor y la discapacidad en individuos con dolor persistente. La utilización de los métodos de representación de movimiento, dentro de estos programas de rehabilitación, podría proporcionar un beneficio añadido en la forma en que los pacientes llegan a aprender los ejercicios propuestos por el clínico.

Los resultados del presente estudio también encontraron que la implementación del entrenamiento de OA e IM mejoró también la fuerza de la región lumbar. La fuerza es una de las variables más relevantes en la práctica deportiva y también, en la rehabilitación. El aumento de la fuerza está relacionado con el aumento del rendimiento deportivo y la prevención en el riesgo de lesiones. Incluir la IM o el entrenamiento de OA, junto con la práctica real, podría presentar beneficios relevantes que deberían tenerse en consideración. Los métodos de representación de movimiento parecen ser seguras y útiles en términos de coste-beneficio. Aunque se necesita más investigación para su transferencia a la población clínica, los métodos de representación de movimiento son un conjunto de herramientas para tener en cuenta en el proceso de aprendizaje motor así como en la mejora de distintas variables físicas. Parece que la OA provocó cambios en el aprendizaje motor más rápidos en comparación con la no aplicación. La estrategia de OA podría utilizarse como guía para enseñar ejercicios de control sensoriomotor lumbo-pélvico.

Artículo 2

Mental practice in isolation improves cervical joint position sense in patients with chronic neck pain: a randomized single-blind placebo trial.

"La práctica mental de manera aislada mejora el sentido de reposicionamiento articular cervical en pacientes con dolor de cuello crónico: un ensayo aleatorizado placebo a simple ciego."

Objetivo: El objetivo principal del presente ensayo clínico fue evaluar si el entrenamiento de OA e IM, de manera aislada, eran capaces de provocar mejoras en el sentido de reposicionamiento articular (SRA) en la columna cervical tanto al finalizar la intervención, como 10 minutos tras finalizar la misma en comparación con un grupo placebo (GP) en pacientes con dolor de cuello crónico inespecífico (DCCI).

Métodos: Un total de 30 pacientes con DCCI fueron asignados aleatoriamente al grupo de OA (n = 10), al grupo de IM (n = 10) o al GP (n = 10). La SRA fue evaluada en los movimientos de flexión, extensión y rotación en ambos planos siendo esta, la variable principal. Esta fue evaluada a través de un dispositivo de retroalimentación visual y fue registrada mediante el cálculo de las desviaciones de la posición objetivo para cada ensayo, en un total de 10 ensayos, en ambos ejes (*x/y*). Los valores de *x* (abscisas) e *y* (ordenadas) se registraron según el sistema de coordenadas cartesianas. Las unidades de medida utilizadas fueron centímetros. Durante la realización de las evaluaciones, ningún *feedback* fue dado a los pacientes respecto a su posición final en cada ensayo.

En adición a esto, se incorporaron un conjunto de variables pre-intervención, a modo de control, para asegurar que todos los pacientes tuvieran una similar condición psicológica y de discapacidad, así como similares niveles de actividad física, capacidad de generar imágenes motoras, e intensidad de dolor inicial. Estas variables control fueron objetivadas a través de la escala tampa de kinesiofobia, el índice de discapacidad cervical, el cuestionario internacional de actividad física, el cuestionario MIQ-R, y finalmente la escala visual analógica.

La tarea consistió en la observación o imaginación, en función del grupo de intervención, de dos movimientos cervicales, en concreto, de dos ejercicios de flexión craneocervical ampliamente utilizados en la rehabilitación mediante los programas de ejercicio terapéutico en pacientes con DCCI. El GP observó un documental sin ninguna presencia de seres humanos.

Resultados: En relación con los resultados, no se encontraron diferencias intergrupales estadísticamente significativas con respecto a las variables control en la evaluación pre-intervención. Es por tanto que todos los sujetos incluidos en los tres grupos tuvieron una condición psicológica y de discapacidad, intensidad de dolor percibido, capacidad de crear imágenes motoras, sincronización y niveles de actividad física similar.

Con respecto a la variable principal, los resultados obtenidos en el plano vertical mostraron que el grupo de OA obtuvo mejoras significativamente mayores que el GP en el SRA durante los movimientos de extensión cervical tanto al final de la intervención ($p = 0{,}001$; $d = 1{,}81$), como 10 minutos después de finalizar la misma ($p = 0{,}004$; $d = 1{,}74$). En adición a esto, también se encontraron diferencias estadísticamente significativas en el movimiento de flexión cervical entre el grupo de OA y el GP, aunque solamente a los 10 minutos después de finalizar la intervención ($p = 0{,}035$; $d = 0.72$). Además, en la comparación entre ambos métodos de representación de movimiento, también en el plano vertical, el grupo de OA obtuvo mejoras significativamente mayores que el grupo de IM en el SRA cervical aunque solamente inmediatamente tras finalizar la intervención en el movimiento de extensión cervical (p

= 0,041; d = 1,17). Con respecto al movimiento cervical de rotación izquierda, tanto el grupo de IM como el de OA fueron significativamente superiores al GP en ambos planos al finalizar la intervención ($p < 0,05$; $d > 0,80$).

Conclusiones: Nuestros resultados sugieren que el entrenamiento de OA es una herramienta de gran potencial para el proceso de entrenamiento sensomotor en el objetivo de provocar un proceso de aprendizaje motor objetivado secundariamente a partir de las mejoras en el SRA durante las primeras etapas de un tratamiento de pacientes con DCCI. Además, la IM también podría ser una técnica de representación de movimiento a considerarse en rehabilitación, pero quizás, con un tiempo de intervención más largo. El potencial terapéutico de la aplicación de los métodos de representación de movimiento durante las primeras fases de rehabilitación de pacientes con DCCI debería considerarse clínicamente.

La alta prevalencia de pacientes con dolor crónico, y especialmente con DCCI, lo convierte en uno de los trastornos musculoesqueléticos más relevantes en las ciencias de la rehabilitación. Es por lo tanto que parece esencial desarrollar e implementar nuevos enfoques en el campo de la rehabilitación. Se ha encontrado que los ejercicios de control sensoriomotor cervical consiguen disminuir la intensidad de dolor y la discapacidad en pacientes con DCCI en comparación con otros tipos de tratamiento. Sin embargo, la implementación clínica de este tipo de ejercicio en un contexto clínico es un reto, debido a su alta complejidad o bien, al propio dolor que puede conducir a los pacientes a no realizarlos. Tanto la IM, como el entrenamiento de OA, proporcionan una alternativa terapéutica simple y de bajo coste que puede ser realizada de forma autónoma por los pacientes. Los resultados de este estudio sugieren que los métodos de representación de movimiento pueden ser una estrategia terapéutica útil en pacientes con DCCI.

Artículo 3

The effects of movement representation techniques on motor learning of thumb-opposition tasks.

"*Los efectos de las técnicas de representación de movimiento en el aprendizaje motor de tareas de oposición de pulgar*"

Objetivos: El objetivo principal de la presente investigación fue evaluar el impacto a corto/medio plazo de la IM y del entrenamiento de OA de manera aislada sobre el aprendizaje motor de una secuencia de posiciones o gestos motores manuales y de complejidad creciente en comparación con una intervención placebo. Además, el objetivo secundario fue evaluar el porcentaje de posiciones totalmente correctas que provocaron las intervenciones de representación de movimiento.

Métodos: Una muestra total de 45 participantes asintomáticos fue asignada aleatoriamente a los tres grupos de intervención; AO: n = 15, IM: n = 15 y grupo de observación placebo (OP): n = 15. Se enseñó una secuencia de 12 posiciones motoras manuales durante 3 días consecutivos (4 posiciones por día). Las principales variables fueron el índice de aciertos, medido a través de porcentaje, así como el tiempo solicitado para colocar la posición manual. La variable secundaria fue las manos efectivas, haciendo referencia al número total de posiciones manuales colocadas de manera completamente correcta. Las variables fueron evaluadas primero inmediatamente post-intervención, 1 semana post-intervención, 1 mes post-intervención y finalmente 4 meses post-intervención.

En relación con las posiciones motoras manuales, el grupo de IM realizó una primera sesión de familiarización el primer día, debido a que tenían primero que integrar una serie de aspectos antes de poder hacer el entrenamiento de representación de movimiento. Tuvieron que memorizar que cada dedo de la mano, en posición anatómica y sin contabilizar los pulgares, tendría asignado un número. Es por tanto que, en la mano izquierda, el índice tendría asignado el valor 2, el dedo corazón el 3, el anular el 4 y finalmente el dedo meñique el número 5. Con respecto a la mano derecha, el dedo meñique tendría asignado el valor 6, el anular el 7, el corazón el 8 y finalmente el índice el 9. Los números fueron dados de manera ordinal (2º, 3º, 4º, etc.) para evitar que durante el entrenamiento de representación de movimiento, los sujetos realizaran una tarea aritmética en lugar de una tarea motora.

Una vez llevada a cabo esta sesión de familiarización, la cual fue independiente de las sesiones de entrenamiento, se llevaron a cabo estas últimas. Las sesiones de entrenamiento fueron realizadas durante 3 días consecutivos, donde el primer día se entrenaron las 4 posiciones de la mano izquierda, el segundo día las 4 de la mano derecha y finalmente, las 4 posiciones bimanuales. Cada posición fue entrenada durante 30 segundos, construyendo la imagen, realizando oposiciones contra el dedo pulgar pero nunca de manera real. Una vez entrenadas las 4 posiciones, y por tanto habiendo pasado 2 minutos, se repitió el entrenamiento de representación de movimiento una segunda vez dando, por tanto, la intervención tuvo una duración total de 4 minutos.

El grupo de OA, realizó este mismo entrenamiento, pero en lugar de construir las imágenes, se les mostró un video de igual duración donde se representaban todas las posiciones manuales en primera persona. Finalmente, al grupo de OP, también se le mostró un video de igual duración que el grupo de OA pero, no se mostraron las posiciones manuales sino un paisaje sin componente humano.

Resultados: Los resultados obtenidos en el presente estudio mostraron que el entrenamiento de OA, mostró una proporción de aciertos significativamente mayor que el grupo de IM y también mayor a la intervención a través del entrenamiento placebo hasta al menos 4 meses después de finalizar la intervención. Sin embargo, es importante señalar que en las posiciones bimanuales, y por tanto las de mayor complejidad, el entrenamiento de OA no fue superior a la IM en la evaluación a la semana después de finalizar la intervención. Además, el entrenamiento en IM fue superior al entrenamiento con observación placebo hasta al menos 1 mes después de la intervención en gestos unimanuales, y hasta al menos 4 meses en gestos bimanuales. Sin embargo, la IM nunca fue superior al entrenamiento de OA.

En relación con el tiempo requerido, los resultados mostraron que el grupo de IM necesitó significativamente más tiempo que los grupos de entrenamiento de OA y observación placebo en el proceso de recordar y colocar los gestos de la mano izquierda y de las dos manos. Sin embargo, para los gestos de la mano derecha, todos los grupos necesitaron un tiempo similar, y por tanto, no se encontraron diferencias entre los grupos de intervención.

Finalmente, en relación con las manos efectivas, contabilizadas como el porcentaje o proporción de posiciones manuales totalmente correctas, el grupo de OA logró una tasa de gestos motores efectivos significativamente mayor que el grupo de IM hasta al menos 4 meses después de la intervención en los gestos motores unimanuales, y hasta al menos 1 mes tras finalizar la intervención en gestos motores bimanuales.

Conclusiones: Este resultado implica que, para gestos motores de mayor complejidad, el entrenamiento de OA no fue superior a la IM a los 4 meses, pero sí lo fue en gestos motores de menor complejidad. El grupo de OA fue superior al grupo placebo en todos los momentos de la evaluación y, además, el grupo de IM fue superior al grupo placebo hasta al menos 1 mes después de finalizar la intervención. Sobre la base de los resultados obtenidos, parece que el entrenamiento con OA conduce a un mayor aprendizaje motor a corto/medio plazo en comparación con la intervención de IM y, por supuesto, en comparación con la intervención placebo. La IM fue superior a la intervención placebo, pero nunca mejor que el entrenamiento de OA.

Artículo 4

The role of movement representation techniques in the motor learning process: a neurophysiological hypothesis and a narrative review.

"El papel de los métodos de representación de movimiento en el proceso de aprendizaje motor: una hipótesis neurofisiológica y una revisión narrativa de la literatura."

Objetivo: El principal objetivo de este artículo fue elaborar y presentar una hipótesis neurofisiológica sobre el papel de los métodos de representación de movimiento a través de la IM y del entrenamiento de OA en el proceso de aprendizaje motor. Existe un conjunto argumental que conformaría una hipótesis neurofisiológica con relación a cómo podrían funcionar los métodos de representación de movimiento en el proceso de aprendizaje motor.

Hipótesis: La representación de movimiento sería capaz de conducir hacia el aprendizaje de nuevas habilidades motoras debido a la congruencia entre la actividad de las redes funcionales neuro-anatómicas de las áreas corticales y subcorticales relacionadas con la planificación, ejecución, ajuste y automatización del movimiento voluntario de la práctica real y la actividad acontecida durante la representación de las imágenes de movimiento. Esta, parece que estaría mediada por un sustrato neural común.

Una mayor congruencia neurofisiológica en las redes sensoriomotoras provocaría un aprendizaje mayor que cuando ocurriera una congruencia neurofisiológica menor. Por tanto, una actividad neurofisiológica de magnitud mayor, producida a través de los métodos de representación de movimiento, conduciría a un mayor aprendizaje motor en comparación con una actividad cerebral de magnitud inferior.

La magnitud de la activación neurofisiológica de las redes sensoriomotoras cortico-subcorticales relacionadas con la planificación, ajuste y ejecución del movimiento podría ser modulada por la influencia de algunas variables clave. Los autores hipotetizan que, dentro de los métodos de representación de movimiento, la IM quizá sea la herramienta más susceptible a la influencia de estas, debido a las características inherentes al proceso de creación y representación de imágenes de movimiento.

Los autores creen que existiría un total de cuatro dominios donde podrían clasificarse el conjunto de variables que podrían modular el efecto de la representación de movimiento. Estos dominios serían: a) dominio físico, b) dominio cognitivo-evaluador, c) dominio motivacional-emocional, y finalmente d) dominio de modulación directa sobre la representación motora.

Además, los autores plantean la hipótesis de que podría existir un sistema de categorización relacionado con la influencia de estas variables durante el proceso de representación del movimiento. Las variables de modulación directa serían primarias debido a que funcionan directamente durante el proceso de representación del movimiento, en directo. El ámbito físico-cognitivo podría influir en las variables de modulación directa, y secundariamente, sobre el proceso de aprendizaje motor, por ejemplo, aumentando los niveles de actividad física para generar más experiencia y así, secundariamente, facilitar la capacidad de generar imágenes motoras o también mejorar la comprensión del gesto motor para facilitar la capacidad de llevar a cabo la representación de dicho movimiento. Finalmente, el dominio motivacional-afectivo o emocional podría influir en todo el conjunto y a todos los niveles debido a su gran peso, por lo que debería considerarse un dominio de tipo transversal.

La activación neurofisiológica cortico-subcortical que ocurre durante la representación de un movimiento, es probable que evoque la formación de una huella mnémica específica y duradera de las representaciones de los movimientos en las fases del aprendizaje motor. Los autores hipotetizan un conjunto de argumentos en relación con la creación de la memoria motora y al proceso de integración de la información visual:

Creemos que el camino neurofisiológico que siguen ambos métodos de representación de movimiento en el proceso de adquisición e integración de la información visual es diferente. Por tanto, van a existir diferentes estrategias en el proceso de creación de la huella motora. La construcción de la imagen motora a través de la IM probablemente sea alimentada en primer lugar, por la actividad continua de la memoria operativa y, en segundo lugar y a través de la actividad del relé episódico, reciba también información de la memoria episódica. Por tanto, la IM requiere necesariamente de estrategias conscientes en el proceso de creación de la imagen de movimiento y, por tanto, de una alta carga cognitiva. Esto podría explicar la fatiga que experimentar los sujetos durante el proceso de construcción de la imagen a través de la IM.

Además, pensamos también que la OA no es necesariamente dependiente del uso de estrategias conscientes debido a la eficiencia que supone que la imagen sea ofrecida de manera externa, con lo que predominantemente hay que retenerla y comprenderla, en lugar de crearla, facilitando el trabajo de la memoria operativa y facilitando, por tanto, la construcción de la huella motora. Por tanto, hay transformación de la imagen y puede haber un trabajo consciente durante la OA pero probablemente requiera una menor carga de trabajo en comparación con el que ocurre con la IM.

Esta actividad neurofisiológica optimizada entre el control ejecutivo central, el cual pertenece a la memoria operativa, y la memoria procedimental es probable que permita la adquisición de estrategias sin ser conscientes de las regularidades que gobiernan el propio proceso de adquisición de las mismas. Es por lo tanto que es probable que, en el proceso de creación de la huella motora a través de la OA, haya una mayor implicación de un aprendizaje de tipo implícito bajo la participación de la memoria procedimental perceptivo-motora.

Finalmente, esto podría también dar respuesta a las diferencias que hay en la susceptibilidad en la influencia de variables físicas, cognitivas, motivacionales-emocionales y de modulación directa entre ambos métodos de representación de movimiento, mostrando una mayor robustez a la influencia el entrenamiento de OA.

Conclusiones: Lo que diferencias ambos métodos de representación de movimiento es que, en el proceso de OA, todos los participantes tienen la misma, precisa, exacta y común información visual aferente que llegaría a nivel central para su procesamiento. Sin embargo, en la IM, existirían variaciones interindividuales que podrían provocar una modulación de su potencial, y, por consiguiente, de su efecto en el aprendizaje debido a que este, depende principalmente de la capacidad de generar imágenes motoras de cada participante aunque reciban todas las personas las mismas instrucciones verbales.

Por tanto, debido a todo esto, los autores hipotetizan que la eficiencia del sistema de neuronas espejo es mayor en el entrenamiento de OA debido a que las imágenes vienen ofrecidas de manera externa, mientras que la IM precisa, necesariamente, de un trabajo interno y autónomo para poder crear, construir y representar las imágenes de movimiento.

Estudio 1

Motor effects of movement representation techniques and cross-education training in recovery and immobilization processes: a systematic review and meta-analysis.

"Efectos motores de los métodos de representación de movimiento y del entrenamiento cruzado en procesos de recuperación e inmovilización: una revisión sistemática y meta-análisis."

Objetivo: El principal objetivo de la presente revisión sistemática y meta-análisis fue evaluar el impacto y los efectos de los métodos de representación de movimiento, así como del entrenamiento cruzado, sobre el comportamiento de distintas variables motoras como el rango de movimiento, la fuerza, la velocidad de la marcha, el equilibrio y el estado funcional en sujetos sanos inmovilizados experimentalmente, en situaciones de lesión con o sin inmovilización y en situaciones de cirugía con o sin inmovilización. Los métodos de representación de movimiento evaluadas fueron la IM, el entrenamiento de OA y la terapia espejo, junto con el entrenamiento cruzado, el cual no es considerado como una técnica de representación motora.

Métodos: Una búsqueda sistemática fue llevada a cabo en las bases de datos Medline (PubMed), Embase, Cinahl y Google Scholar, así como una búsqueda dentro de los artículos encontrados en las citadas bases de datos, con el objetivo de incluir todos los artículos publicados sobre el tema en cuestión. Se llevó a cabo el análisis independiente y pareado del riesgo de sesgo a través del *Handbook* para revisiones sistemáticas del grupo Cochrane obteniéndose un alto nivel de concordancia entre evaluadores (κ = 0.813). Además, para el análisis cualitativo se utilizó la clasificación de los niveles de evidencia de acuerdo con la clasificación de las recomendaciones, valoración, desarrollo y evaluación denominado GRADE.

Resultados: Un total de 34 estudios fueron incluidos y 13 meta-análisis fueron llevados a cabo. Con respecto a los participantes inmovilizados, en los sujetos sanos inmovilizados experimentalmente, la IM mostró resultados significativos con baja calidad de la evidencia en cuanto al mantenimiento de la fuerza (diferencia de medias estandarizada [SMD] = 2,73; intervalo de confianza [IC] del 95%: 1,91 a 3,55; valor Q = 0,06; p = 0,8) y del rango de movilidad (SMD = 0,7; IC del 95%: 0,05 a 1,35; valor Q < 0,001; p = 0,99). Con respecto al proceso sin inmovilización, dos meta-análisis mostraron que los métodos de terapia espejo (SMD = 2,33; IC del 95%: 0,33 a 4,34; valor Q = 6,76; p = 0,01; I^2 = 85%) y de IM (SMD = 1,21; IC del 95%: 0,11 a 2,3; valor Q = 6,47; p = 0,04; I^2 = 69%) mostraron cambios estadísticamente significativos en el mantenimiento del rango de movimiento en pacientes con lesiones sin cirugía pero con muy baja calidad de la evidencia. Además, los resultados también mostraron que la IM provocó un mantenimiento significativamente mayor de la fuerza (SMD = 1,26; IC del 95%: 0,71 a 1,8; valor Q = 2,07; p = 0,36; I^2 = 3%) y de la velocidad de la marcha (SMD = 0,56; IC del 95%: 0,08 a 1,03; valor Q = 0,37; p = 0,83; I^2 = 0%) en los pacientes que se sometieron a una cirugía, con baja calidad de la evidencia. Sin embargo, no se encontraron resultados significativos con respecto al rango de movimiento (SMD = 0,7; IC del 95%: -0,89 a 2,29; valor Q = 3,42; p = 0,06; I^2 = 71%).

El entrenamiento de OA mostró que en adición al tratamiento habitual obtuvo resultados significativamente más altos con respecto al mantenimiento del estado funcional (SMD = 0,74; IC del 95%: 0,34 a 1,14; valor Q = 3,54; p = 0,32; I^2 = 15%) y del equilibrio (SMD = 0,61; IC del 95%: 0,18 a 1,03; valor Q = 3,92; p = 0,17; I^2 = 24%) en comparación con el tratamiento habitual de manera aislada con baja calidad de evidencia.

El entrenamiento cruzado mostró un mantenimiento de la fuerza en pacientes sometidos a cirugía (SMD = 0,65; IC del 95%: 0,33 a 0,96; valor Q = 3,21; p = 0,52; I^2 = 0%), con moderada calidad de evidencia; sin embargo, esto no se encontró en individuos sanos inmovilizados experimentalmente (SMD = 1,85; IC del 95%: -0,07 a 3,77; valor Q = 14,82; p < 0,01; I^2 = 87%). Finalmente, la terapia espejo no mostró resultados significativos en el mantenimiento del rango de movilidad después de una cirugía sin inmovilización (SMD = 0,46; IC del 95%: -0,06 a 0,98; valor Q = 7; p = 0,07; I^2 = 57%), ni la IM en el mantenimiento de la fuerza después de una cirugía seguida de un proceso de inmovilización (SMD = 0,13; IC del 95%: -0,37 a 0,64; valor Q = 0,9; p = 0,34).

Conclusiones: Los métodos de representación de movimientos, así como el entrenamiento cruzado, son un conjunto de herramientas de muy bajo coste que han mostrado tener un impacto significativo en la mejora de la función motora durante los procesos de recuperación e inmovilización. El entrenamiento de OA y el entrenamiento cruzado parecen beneficiar a los pacientes con lesión que se someten a una cirugía, mientras que la IM y la terapia espejo parecen funcionar mejor en los individuos sanos que se someten a una inmovilización experimental, así como en las lesiones que no requieren cirugía.

Es por lo tanto que los métodos de representación del movimiento y el entrenamiento cruzado han mostrado tener un impacto significativo en la mejora de diversas variables motoras en particular, y en el mantenimiento de la condición física en general, durante los procesos de inmovilización experimental en individuos sanos, en pacientes con lesiones que no requieren de cirugía y en procesos quirúrgicos que requirieron o no inmovilización. A pesar de esto, todavía se necesitan más investigaciones debido a la baja calidad de la evidencia.

DISCUSIÓN

6. Discusión

Los hallazgos encontrados en los estudios incluidos en la presente tesis doctoral, tanto de carácter básico (artículos 1 y 3), como clínico (artículo 2 y estudio 1) , coinciden con un importante número de estudios publicados en la última década (Beinert et al., 2019; Gatti et al., 2013; González-Rosa et al., 2015; Moukarzel et al., 2019) y además, añaden nueva información relevante con respecto a algunos aspectos de la evaluación y análisis comparativo entre los métodos de representación de movimiento con respecto al proceso de aprendizaje motor. A continuación se discute en profundidad los resultados obtenidos según objetivos planteados en la presente tesis doctoral.

6.1 Aprendizaje Motor en la Región Lumbo-Pélvica

Los resultados del artículo 1 han mostrado que, dentro de los métodos de representación de movimiento, el entrenamiento de OA, en adición a un programa de ejercicios real, condujo a un proceso de aprendizaje motor con mayor rapidez en comparación a no incluirlo, evaluado y objetivado a través de la adquisición, mejora y consolidación de distintas tareas y ejercicios de control sensoriomotor en la región lumbo-pélvica en sujetos asintomáticos. Sin embargo, este cambio no fue estadísticamente superior a los encontrados durante la aplicación de la IM.

Los ejercicios de control sensoriomotor incluyen un complejo proceso que envuelve no solamente la ejecución del movimiento voluntario, sino que también requiere de un complejo sistema de planificación y programación del movimiento, un ajuste del tono, de la fuerza y de la sincronización de otros parámetros de movimiento (Latash et al., 2010). La realización de un gesto motor, es decir, la experiencia o la práctica real de este es incuestionablemente un aspecto fundamental para adquirir y consolidar nuevos gestos motores. De hecho, el grupo que solamente realizó los ejercicios sin la presencia de los métodos de representación de movimiento mostró cambios intragrupo estadísticamente significativos también. A través de la práctica, se consiguen mejoras intrínsecas del propio movimiento y también parece que consolida y estabiliza una huella motora gobernada por la memoria procedimental, un tipo de memoria implícita, o no declarativa, subyacente al proceso de aprendizaje asociativo (Robertson et al., 2004). Los métodos de representación de movimiento producen un conjunto de representaciones corticales, así como unos sustratos neurales similares a los que produce la práctica real de un movimiento cualquiera, haciendo que tanto la IM, como el entrenamiento de OA, puedan tener un papel relevante en el proceso de aprendizaje motor (Ehrsson et al., 2003; Naish et al., 2014).

Frank et al. (2014) mostraron que al añadir un entrenamiento de IM a la realización de un entrenamiento de práctica real, se crearon mayores adaptaciones cognitivas, así como mayores mejoras en la representación motora en comparación a realizar los ejercicios de manera aislada. Un hallazgo muy interesante, y que podría estar en concordancia con estos hallazgos, es el encontrado por Mulder et al. (2005) donde hallaron que la IM pareció ser más efectiva sobre el aprendizaje de gestos motores previamente conocidos en contraposición a gestos totalmente novedosos. Los ejercicios propuestos en nuestro estudio de control sensoriomotor incluyeron gestos con alta calidad de movimiento, así como de gran dificultad siendo probable que esta complejidad, presente en los movimientos lumbo-pélvicos entrenados en el presente estudio, favorezca al entrenamiento de OA en comparación con la IM con respecto a la velocidad con respecto al proceso de adquisición de los mismos. Neurofisiológicamente, en presencia de gestos motores con alta complejidad, la ausencia de un aporte visual, así como un contexto adecuado, es probable que influya en la actividad de las áreas relacionadas con la planificación del movimiento voluntario. Algunos autores como Mattar & Gribble

(2005) o Stefan et al. (2005) han mostrado la relevancia del entrenamiento de OA en la generación de una huella motora como prerrequisito del aprendizaje motor.

6.2 Aprendizaje Motor en la Región Cráneo-Cervical

Con respecto a los pacientes con DCCI se encontró en el artículo 2 que tanto el entrenamiento de OA, como la IM, ambas de manera aislada, fueron superiores a una intervención placebo en la mejora del SRA como medida de resultado subyacente a un proceso de aprendizaje motor en la región cráneo-cervical. Esto se encontró durante las evaluaciones de los movimientos en el mismo plano de la observación e imaginación (plano vertical: movimientos de flexo-extensión) aunque no en las desviaciones en el eje horizontal.

En adición a esto, el entrenamiento de OA produjo mejoras significativamente mayores del SRA en comparación con la IM pero en el movimiento de extensión y exclusivamente en la evaluación de las desviaciones del plano vertical. Finalmente, ambos métodos de representación de movimiento, de manera aislada, mostraron mayores mejoras del SRA tanto en el plano vertical, como en el plano horizontal, en el movimiento de rotación izquierda en comparación con una intervención placebo. Sin embargo, esto no se encontró en el movimiento de rotación derecha.

Estos hallazgos fueron encontrados de manera similar en el estudio llevado a cabo por Beinert et al. (2019) aunque los movimientos elegidos por estos investigadores fueron distintos a los elegidos en nuestro estudio. Los movimientos que elegimos para llevar a cabo esta investigación fueron movimientos delicados, de alta precisión y solamente realizados en el plano vertical.

A la hora de justificar los resultados encontrados, y viendo que los resultados más robustos se encontraron en la evaluación de las primeras etapas del aprendizaje motor en el mismo plano del movimiento, necesitamos analizar el papel de las neuronas espejo y su relación en el proceso de reconocimiento de las acciones. Rizzolatti et al. (2001) establecieron la hipótesis de coincidencia directa. Según esta hipótesis, el entrenamiento de OA es capaz de provocar una activación automática en el observador de las mismas áreas cerebrales relacionadas con la planificación y ejecución del movimiento voluntario real de la acción observada. Debido a que se conoce el resultado de la activación de estos sustratos neuronales durante la ejecución de una acción, la observación permite al observador comprender aquello que está observando a través de un mecanismo específico de emparejamiento observación-ejecución. Tal vez debido a la gran complejidad de las tareas de control sensoriomotor cráneo-cervical, junto con el hecho de que solamente se aplicaron los métodos de representación de movimiento en un solo plano, planteamos la hipótesis de que la activación de los sustratos neuronales está relacionada con la planificación y ejecución de movimientos voluntarios específicos en dicho plano (vertical). Esta hipótesis explicaría las mejoras en la SRA en los movimientos del mismo plano representado pero no en el plano horizontal. Sin embargo, esta explicación es solamente una aproximación hipotética de corte neurofisiológica debido a que la actividad cerebral de los pacientes no pudo ser observada directamente. Sin embargo, en base a los hallazgos encontrados en el movimiento de rotación izquierda, los autores también hipotetizamos que podría haber un mecanismo de plano de movimiento inespecífico para explicar este resultado. Creemos, no solamente en base a los resultados obtenidos sino también a los hallados por Papadelis et al. (2007), que los métodos de representación de movimiento proporcionan una referencia corporal de posición interna que, secundariamente, mejora el control espacio-temporal de la posición del cuerpo en el espacio durante un movimiento dinámico, un aspecto crítico del proceso de adquisición y aprendizaje motor. Papadelis et al. (2007) formularon la hipótesis que los métodos de representación de movimiento son capaces de conducir a una mejor integración de las acciones motoras debido a una mejor y más precisa referencia corporal interna a pesar de la falta de movimiento real. Es posible que esta mejor referencia interna de la posición de la cabeza con respecto a la posición del cuerpo pueda explicar los resultados positivos obtenidos en la rotación cervical izquierda, a pesar de que los gestos mentales realizados estaban centrados en otro plano de movimiento.

Además, los ejercicios de flexión cráneo-cervical seleccionados también podrían influir en las diferencias encontradas entre el entrenamiento de OA y el de IM. Los ejercicios de flexión cráneo-cervical son difíciles de representar o construir debido a que son movimientos de alta dificultad y precisión. Por ejemplo, investigaciones anteriores han mostrado que la complejidad y la familiaridad del movimiento están relacionadas con el rendimiento de la IM (Paris-Alemany et al., 2019). Este grupo de intervención podría haber sido influenciado por la dificultad en el proceso de construcción o representación de la imagen motora. Además, la IM es menos efectiva en personas con menor capacidad para realizarla (Patterson et al., 2006) y finalmente, los pacientes con dolor crónico tienen una menor capacidad para representar o construir imágenes de movimiento, lo que también podría haber influido en nuestros resultados (Breckenridge et al., 2019; La Touche et al., 2018). Por lo tanto, teniendo en cuenta todas estas variables, el entrenamiento de OA pudo mostrar mejores resultados que la IM debido a que, para la realización de esta última, se requiere de un esfuerzo dedicado a la tarea significativo, así como de una serie de habilidades y capacidades, que los pacientes podrían no haber logrado o tenido.

6.3 Aprendizaje Motor en Tareas Manuales

Los resultados obtenidos en el artículo 3 respecto a la evaluación y análisis comparativo de los métodos de representación de movimiento, de manera aislada, a corto-medio plazo en el proceso de aprendizaje motor, mostraron que el entrenamiento de OA obtuvo una significativa mayor proporción de aciertos que la intervención de IM, así como la intervención placebo hasta al menos 4 meses después de finalizar la intervención. Además, el entrenamiento de IM fue significativamente superior a la intervención placebo hasta, al menos, 1 mes después de la intervención en gestos unimanuales y hasta al menos 4 meses en los bimanuales. Sin embargo, la IM nunca fue mejor que el entrenamiento de OA. Con relación al tiempo requerido, los resultados mostraron que el grupo de IM necesitó significativamente más tiempo que los grupos placebo y de OA para recordar y realizar los gestos con la mano izquierda y las dos manos. Sin embargo, para los gestos con la mano derecha, todos los grupos utilizaron un tiempo similar. Con respecto al porcentaje de posiciones manuales totalmente correctas, el entrenamiento de OA logró una tasa de gestos motores manuales efectivos significativamente mayor que el grupo de IM hasta, al menos, 4 meses después de la intervención en gestos unimanuales y hasta 1 mes después de la intervención en gestos bimanuales. Este resultado implica que para gestos más complejos, el entrenamiento de OA no fue superior al de IM a los 4 meses, pero fue superior en gestos de menor complejidad. El grupo de OA fue superior al grupo de intervención placebo en todos los momentos de la evaluación, y el grupo de IM fue superior al grupo de intervención placebo hasta, al menos, 1 mes después de la intervención.

En el estudio realizado por Gatti et al. (2013) también se realizó solamente una sesión de intervención, por lo que únicamente se aplicó la fase rápida, descrita por Doyon & Benali (2005) y Grèzes et al. (2003), del proceso de aprendizaje motor. Sus resultados están en línea con los obtenidos en el presente estudio, ya que encontraron que el entrenamiento de OA era más efectivo que la IM en el proceso de aprendizaje motor de gestos complejos a corto plazo.

Los resultados obtenidos respaldan estos hallazgos y también muestran que el entrenamiento de OA es más efectivo que la IM en el aprendizaje motor hasta al menos 4 meses después de una sesión de entrenamiento motor de posiciones motoras unimanuales, y hasta al menos 1 mes después en posiciones bimanuales. Estos hallazgos también estaban en concordancia con los encontrados por Gonzalez-Rosa et al. (2015). Estos autores encontraron que el entrenamiento de OA también era más efectivo, de manera aislada, que la IM en la promoción y consecución del proceso de aprendizaje temprano de una nueva y compleja tarea motora de coordinación.

Con respecto a la justificación de los resultados, Gatti et al. (2013) han argumentado que el entrenamiento de OA, tiene un mayor impacto que la IM debido a que el sistema de neuronas espejo, parece funcionar de forma más precisa, eficiente y adecuada a través de la observación. Esto parece tener una explicación, por tanto, neurofisiológica. La corteza premotora ventral, un área ampliamente involucrada en la planificación del movimiento voluntario, recibe aferencias de la corteza estriada y extraestriada (Pardo-Vázquez & Acuña, 2014); por lo tanto, el entrenamiento de OA podría causar una mayor activación neurofisiológica funcional que la provocada por la construcción de imágenes motoras.

Además, el acto de representar y construir imágenes de movimiento podría variar de forma interindividual, es decir, entre personas y, por lo tanto, podría estar relacionado con algunas variables tales como el nivel de actividad física, la propia capacidad de generar imágenes motoras, la complejidad de la tarea que se ha de imaginar, el tiempo de la imaginación, el esfuerzo requerido para la tarea o la viveza de la imagen, entre otras (Callow & Hardy, 2004; Di Corrado et al., 2014; Goss et al., 1986; Isaac & Marks, 1994; Robin et al., 2007). Por lo tanto, todos los participantes del grupo de entrenamiento de OA tenían un modelo de referencia exacto, preciso, inequívoco y específico de las posiciones motoras demandadas mientras que el grupo de IM únicamente poseía su propia capacidad de generar, representar y construir imágenes de movimiento.

Estas dos son las principales justificaciones de los resultados del artículo 3. Sin embargo, también planteamos una tercera hipótesis, y es que otro posible factor podría explicar las diferencias observadas. Es el caso de la variable fatiga percibida debida a la IM. Roure et al. (1999) y Guillot et al. (2004) han reportado que la aplicación de los métodos de representación de movimiento son capaces de inducir y causar fatiga mental (operativizando el término mental como no-físico, entendiendo la mente a su vez como un conjunto de conductas verbales privadas y no un lugar donde ocurren los pensamientos o las representaciones de movimiento), así como una dificultad para mantener la atención, sobre todo la IM. Quizá la pérdida de atención, así como la presencia de fatiga percibida, fuese mayor en el grupo de IM en comparación con el grupo de OA pudiendo conducir a peores resultados en este grupo. Sin embargo, debido a que no se evaluó la fatiga percibida, esto solamente puede considerarse como otra hipótesis añadida a la justificación de los resultados obtenidos. Esto fue también argumentado anteriormente por Buccino (2014), el cual defiende que la IM tiene algunos límites intrínsecos que el entrenamiento de OA no exhibe porque la IM es una herramienta más exigente, en términos de atención y concentración, en comparación con el entrenamiento de OA.

6.4 Planteamiento de una Hipótesis Neurofisiológica y una Revisión Narrativa

La hipótesis neurofisiológica con perspectiva bioconductual, se llevó a cabo para intentar primero, compilar el conjunto de justificaciones y argumentaciones que elaboramos para poder dar respuesta a los resultados obtenidos en la presente tesis doctoral, y segundo, para poder establecer una construcción teórica, específicamente de las diferencias posibles en el proceso de creación de representaciones mnémicas, es decir, del proceso de integración de la información visual en la formación de la memoria motora como prerrequisito del aprendizaje motor.

Con respecto a la primera intención del artículo 4, esta hipótesis con revisión muestra cómo los resultados obtenidos en los estudios de esta tesis doctoral están en concordancia con otras investigaciones y las justificaciones anteriormente aportadas, también están soportadas por un gran número de estudios. Por ejemplo, en el artículo 1, 2 y 3 se argumentó que los gestos motores complejos estaban representados de manera facilitada si se aporta un input visual, en comparación con crear o representar la imagen de manera activa en ausencia de este. Además, también se argumentó que, mientras en la OA todas las personas obtienen el mismo input visual, la IM, incluso a pesar de que las indicaciones verbales son las mismas, en estas puede haber diferencias interindividuales debido a que habrá un número de variables que pueden intervenir en la construcción de las imágenes motoras. Esto se recoge en este estudio de hipótesis.

Creemos que existe un total de cuatro dominios donde pueden clasificarse el conjunto de variables que podrían modular el efecto de la representación de movimiento. Estos dominios son el dominio físico, el dominio cognitivo-evaluador, el dominio motivacional-afectivo y el dominio de modulación directa sobre la representación motora **(Tabla 1)**. Incluso además planteamos la hipótesis que podría existir un sistema de categorización relacionado con la influencia de estas variables durante el proceso de representación del movimiento. Todas estas suposiciones de actuación y clasificación están basadas en hallazgos de la literatura científica.

Tabla 1. Variables moduladoras del proceso de representación de movimiento

Dominio	Variables	Influencia
Físico IM * * * OA *	-Niveles de actividad física	-Un mayor nivel de actividad física podría generar una mayor facilidad en la construcción del movimiento gracias a la experiencia, el desarrollo, y la elaboración de esquemas motoras de forma habitual
	-Fatiga percibida	-La presencia de altos niveles de fatiga puede alterar la atención, limitando así la construcción cerebral del movimiento
	-Alteraciones en la integración sensoriomotora	-La presencia de alteraciones somatosensoriales pueden generar esquemas sensoriomotores aberrantes que, secundariamente, podrían afectar a la construcción del movimiento. Esto podría conducir a una disminución de la capacidad de generar imágenes mentales motoras

Cognitivo-Evaluador IM * * * OA *	-Comprensión del gesto motor y de las instrucciones verbales	-La comprensión de un movimiento no elaborado físicamente, puede mejorar las fases de planificación del movimiento a nivel cerebral ya que disminuyen los limitantes emocionales y cognitivos
	- Contexto	-La elaboración del movimiento en contexto familiares y específicos podrían facilitar la observación y la imaginación
	-Funcionamiento de la memoria de trabajo	-Un mejor funcionamiento de la memoria de trabajo podría aumentar la capacidad de recolección de la información provista así como su posterior consolidación hacia la memoria a largo plazo facilitando así, el proceso de aprendizaje motor
	-Niveles de auto-eficacia	-Una mayor auto-percepción de capacidad de generar imágenes mentales motoras podría favorecer la propia habilidad de construcción cerebral del movimiento
	-Niveles de atención	-El mantenimiento de la atención podría facilitar la construcción cerebral de un movimiento y el esfuerzo mental dedicado al mismo

	-Expectativas	-Las expectativas sobre los efectos de las herramientas de entrenamiento cerebral podrían influir sobre la eficiencia en el proceso de aprendizaje motor
	-Percepción de dificultad	-Una mayor percepción de la dificultad podría conducir a una reducción de la capacidad de generar imágenes motoras y por lo tanto, podría empeorar el aprendizaje motor
Motivacional-Emocional IM * * * OA * * *	-Motivación (razones, intención y deseos)	-Mayores niveles de motivación van a conducir directamente hacia una mejor predisposición hacia proceso de aprendizaje, y por tanto, sobre los efectos de las herramientas de entrenamiento cerebral
	-Miedo al movimiento	-Mayores niveles de kinesiofobia pueden conducir a una interrupción de los procesos de representación motora, pudiendo minimizar o inhibir el proceso de aprendizaje motor
Modulación directa IM * * * OA *	-Capacidad de crear imágenes motoras	-La eficacia de la IM puede depender directamente de la capacidad de construir imágenes motoras. Esta puede ser influenciado por el resto de dominios
	-Sincronización	-Una mayor congruencia en el tiempo

		empleado durante la práctica real y durante la representación del movimiento podría facilitar el proceso de aprendizaje motor
	-Actividad del Sistema Nervioso Autónomo	-Una mayor actividad neurovegetativa podría indicar una mayor actividad neurofisiológica de las redes corticales-subcorticales sensoriomotoras. Esto podría indicar un mayor esfuerzo dedicado a la tarea, así como una mayor atención y menor fatiga durante la representación motora, favoreciendo el aprendizaje motor

*Abreviaturas: IM: Imaginería motora; OA: Observación de acciones; *Baja susceptibilidad; **Moderada susceptibilidad; ***Alta susceptibilidad.*

para generar más experiencia y así, secundariamente, facilitar la capacidad de generar imágenes motoras o también mejorar la comprensión del gesto motor para facilitar la capacidad de llevar a cabo la representación de dicho movimiento. Finalmente, el dominio motivacional-emocional podría influir en todo el conjunto y a todos los niveles debido a su gran peso, por lo que debería considerarse un dominio de tipo transversal.

La activación neurofisiológica cortico-subcortical que ocurre durante la representación de un movimiento, es probable que evoque la formación de una huella de memoria específica y duradera de las representaciones de los movimientos en las fases del aprendizaje motor. Los autores hipotetizan un conjunto de argumentos en relación con la creación de la memoria motora y al proceso de integración de la información visual:

Por ejemplo, con respecto a las variables cognitivo-evaluadoras, mayores esfuerzos durante la construcción y representación de imágenes motoras condujeron a mayores cambios hemodinámicos a nivel cerebral (Wriessnegger et al., 2017). En cuanto al dominio físico, hay extensa literatura científica que apoya su relevancia en el proceso de representación del movimiento. Por ejemplo, los atletas con altos niveles de actividad física muestran una mayor capacidad para generar y construir imágenes motoras en comparación a atletas amateurs con unos niveles más bajos de actividad física (Di Corrado et al., 2014; Paris-Alemany et al., 2019; Williams et al., 2015). En el estudio llevado a cabo por La Touche et al. (2018), se encontró que los pacientes con dolor lumbar crónico mostraron una correlación negativa y moderada entre el nivel de kinesiofobia y la capacidad de generar imágenes motoras tanto cinéticas como visuales. Además, también encontraron que la capacidad de generar imágenes motoras se veía afectada en los pacientes con dolor lumbar crónico en comparación con los participantes sanos. Esto también fue encontrado por otro grupo de investigación (Pijnenburg et al., 2015). Con respecto a las variables de modulación directa, donde quizá la principal crítica es que parece un cajón de sastre, debido a la naturaleza de las variables que la forman, parece que el proporcionar un input visual antes de realizar una tarea de construcción de imágenes motoras facilita y causa una mayor actividad neurofisiológica que si se realiza de manera aislada (Sakamoto et al., 2009; Taube et al., 2015; Vogt et al., 2013). Además, se ha encontrado que la viveza en el proceso de creación de las imágenes de movimiento afecta al aprendizaje motor, mostrando cambios más significativos en aquellos participantes que presentaban una imaginación con mayor viveza (Isaac & Marks, 1994).

Una de las variables más importantes en esta categoría es la respuesta del sistema nervioso autónomo, donde Cuenca-Martínez et al. (2018) encontraron que la complejidad del movimiento, la intensidad del esfuerzo y los niveles de actividad física podrían influir en la actividad neurovegetativa en el proceso de generación y construcción de imágenes motoras. Por último, en lo que respecta a la sincronización, también conocida como cronometría mental, algunos estudios han mostrado que los movimientos desconocidos, poco comunes e incómodos pueden dar lugar a diferencias entre el tiempo empleado en la ejecución imaginada y en la ejecución real (Parsons, 1994; Rieger, 2012). Todos estos estudios apoyan la presencia de todas las variables anteriormente citadas, nosotros las categorizamos y le proporcionamos una construcción teórica hipotética.

Con respecto al establecimiento de las diferencias en el proceso de creación de representaciones mnémicas, es decir, en el proceso de integración de la información visual en la formación de la memoria motora como prerrequisito del aprendizaje motor, el aprendizaje de conductas motoras complejas está basado en la adquisición de representaciones neurales de los requisitos mecánicos y de los parámetros del movimiento (coordinación, fuerza, velocidad, etc.) (Mattar & Gribble, 2005).

El estudio de Mattar & Gribble (2005) mostró que la adquisición de las representaciones neuronales sobre propiedades de un gesto motor a través de la observación, fue un proceso no dependiente del uso de estrategias conscientes, sino que se basó en las propiedades implícitas del sistema sensoriomotor. Este es uno de los hallazgos principales que da coherencia a la presente hipótesis. Además, Mattar & Gribble (2005) también encontraron que las personas sometidas al entrenamiento de OA, se beneficiaron de los efectos de la observación incluso cuando los sistemas atencionales estuvieron ocupados en una tarea distractora, en este caso aritmética. Los autores sugirieron que los sistemas de atención podrían influir y estar involucrados, pero parece que no son críticos para el proceso de aprendizaje mediado por la observación. Quizá, la tarea de distracción matemática demandó un tipo de tarea cognitiva específica, pero dejó libre otros tipos de mecanismos de cognición suficientes para la creación y mantenimiento de las estrategias motoras.

Sin embargo, se ha reportado que puede haber un proceso de aprendizaje motor tanto de manera explícita, como de manera implícita (Destrebecqz & Cleeremans, 2001), es decir, se puede utilizar el conocimiento declarativo para el proceso de creación de un conjunto de reglas para conducir hacia el aprendizaje motor o bien, existe la capacidad de obtener conocimientos o información en torno a la adquisición de un conjunto de habilidades motoras sin la consciencia de las regularidades que gobiernan dicho proceso de adquisición (Jongbloed-Pereboom et al., 2019). Este último, bajo la participación de la memoria implícita o procedimental, puede ocurrir a la vez que la práctica (definido como "en línea") o fuera de ella (Meissner et al., 2016). En la fase cognoscitiva del aprendizaje motor, donde la demande cognitiva es muy elevada está especialmente involucrado el aprendizaje explícito, es decir, el aprendizaje explícito impone grandes exigencias a la memoria de trabajo (Steenbergen et al., 2010), mientras que el aprendizaje implícito, se produce en ausencia de la fase cognoscitiva, y por tanto, no depende de esta última (Jongbloed-Pereboom et al., 2019) **(Figura 3)**.

Finalmente, para terminar de entender la estructura clave donde pivota esta hipótesis, ampliamos la información con respecto a la estructura 'memoria de trabajo'. Esta, es un depósito donde existe un complejo proceso de almacenamiento activo donde la información es susceptible de manipulación intraindividual. De hecho, Postle (2006) argumentó que en la memoria de trabajo, la información se retiene de manera consciente para poder ser manipulada posteriormente y guiar así las conductas. Una de las estructuras cerebrales relacionada con la memoria de trabajo en el aprendizaje de secuencias motoras implícitas es la corteza prefrontal dorsolateral (Bo et al., 2011), de hecho, se ha observado que la interrupción del funcionamiento de la corteza prefrontal dorsolateral contralateral afecta y empeora el aprendizaje de una secuencia motora de manera real (Pascual-Leone, Wassermann, Grafman, & Hallett, 1996).

Además, el artículo 4 no solamente incluye una hipótesis neurofisiológica, sino también realizamos una revisión narrativa para ver el impacto de los métodos de representación de movimiento sobre el aprendizaje motor.

En total revisamos 21 artículos que versaron sobre los métodos de representación de movimiento sobre el aprendizaje motor. Los hallazgos encontrados mostraron que tanto en población clínica, como en sujetos asintomáticos, incluir métodos de representación de movimiento como el entrenamiento de OA e IM provoca mayores efectos en el proceso de aprendizaje motor que no incluirlos y por tanto, que la práctica física de manera aislada.

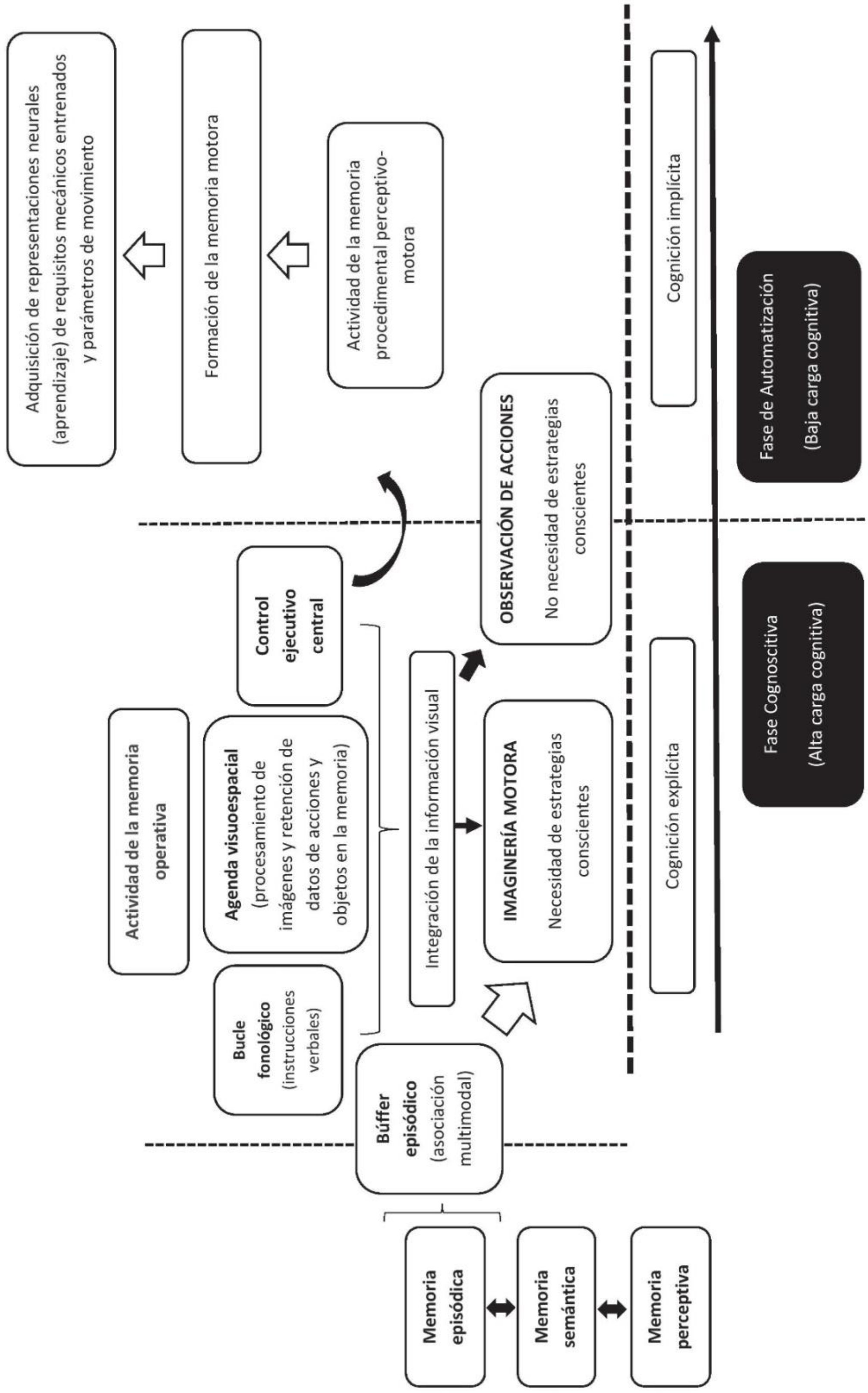

Figura 4. *Hipótesis sobre el funcionamiento y adquisición de representaciones mnémicas.*

Todos estos hallazgos anteriormente descritos, parecen dar solidez a nuestra hipótesis neurofisiológica, aunque con perspectiva bioconductual, con respecto a las posibles diferencias de integración de la información visual a la hora de construir y representar imágenes de movimiento.

6.5 Métodos de Representación de Movimiento sobre Procesos de Reaprendizaje y Reacondicionamiento Motor

A través de la evaluación del cambio en la función motora, se pueden evaluar indirectamente algunos aspectos clave como los procesos de reaprendizaje motor tras una lesión o una inmovilización, es decir, tras el desuso mantenido. El proceso de recuperación puede evaluarse a partir de los valores fisiológicos de algunas variables clave del sistema sensoriomotor tales como la fuerza, la velocidad, el equilibrio y el estado funcional, previniendo o minimizando un proceso de desuso debido a una lesión, una intervención quirúrgica o una situación de inmovilización experimental.

El mantenimiento de la condición física, y por tanto del estado específico de algunas variables motoras tras un proceso de inmovilización experimental o tras un proceso clínico con o sin cirugía (por ejemplo, la recuperación de la fuerza, el reaprendizaje motor mediante la recuperación del rango de movilidad activo, el mantenimiento del equilibrio o la velocidad), podría revelar indirectamente el estado de la función de la región del cerebro en relación con la planificación, automatización y ejecución del movimiento voluntario, así como las áreas implicadas en la generación de fuerza (por ejemplo, la corteza motora primaria, la corteza premotora, el área motora suplementaria, los ganglios de la base o el cerebelo) (Jeannerod, 1995; Ranganathan et al., 2004).

Ranganathan et al. (2004) encontraron que la recuperación de la fuerza se origina a través de un proceso neuroplástico adaptativo en el desempeño de la actividad de las regiones corticales, lo que hace que las unidades motoras generen tanto una mayor intensidad, como un mayor reclutamiento del conjunto de unidades motoras que normalmente permanecerían sin actividad. Además, Moukarzel et al. (2019) hallaron recientemente que la IM podría ser relevante para promover el reaprendizaje motor, así como la recuperación motora en pacientes con problemas de rodilla. Estos autores, así como otros grupos de investigación (Meier et al., 2008; Mizner et al., 2005), han argumentado que la combinación de la atrofia muscular, junto con un déficit de activación neuromuscular, son los principales factores que contribuyen a la reducción de la fuerza muscular. A través de los métodos de representación de movimiento, es probable que se produzca un proceso neuroplástico adaptativo de reorganización cortical, mejorando así la preparación para el movimiento, dando lugar a un aumento del reclutamiento motor y de la sincronización de las unidades motoras a nivel periférico (Moukarzel et al., 2019). Este resultado es lo que podría explicar, secundariamente, la mejora de las variables motoras periféricas tales como la fuerza, velocidad de la marcha o el rango de movilidad activo.

Por lo tanto, como postulan Moukarzel et al. (2019), parece que los métodos de representación del movimiento podrían aumentar, potenciar y mejorar la preparación del movimiento voluntario mediante un proceso de reorganización a nivel cortical, provocando, indirectamente, una mayor activación muscular voluntaria, rango activo de movimiento, fuerza, equilibrio, etc. De hecho, se han propuesto un gran número de teorías que han tenido por objeto ofrecer una explicación del efecto de los métodos de representación del movimiento en la actividad de los músculos periféricos.

El estudio realizado por Christakou et al. (2007) muestra algunas de estas teorías de manera excepcional. Por ejemplo, describen la hipótesis ideomotora de Carpenter, (1894) de finales del siglo XIX o la teoría psico-neuromuscular de Jacobson en los años

30 (Jacobson, 1930). Esta última fue posteriormente contrastada por Hale (2016). También existe la hipótesis del entrenamiento neuronal, propuesta por los autores Sale y Enoka & Fuglevand, la cual sugiere que los cambios a nivel central son los que causan un aumento a nivel periférico de la actividad muscular (Christakou et al., 2007; Sale, 1988). En adición a esto, Jowdy & Harris (2016) encontraron un aumento significativo de la actividad muscular durante las tareas de representación de movimientos evaluadas mediante electromiografía de superficie. Para finalizar, se ha encontrado que la construcción de imágenes de movimiento podría conducir a una mejor representación del proceso de generación de fuerza motora a nivel central, es decir, en el sistema central de programación y planificación de la corteza cerebral (Annett, 1995; Jeannerod, 1995). Todo esto podría explicar los resultados del estudio 1, es decir, podría dar respuesta al por qué el entrenamiento mediante métodos de representación de movimiento podría tener un impacto a nivel central y, por consiguiente, a nivel periférico.

CONCLUSIONES

7. Conclusiones Generales

Los resultados de las investigaciones incluidas en la presente tesis doctoral muestran que las técnicas de representación de movimiento, en combinación con la práctica real o de manera aislada, condujeron a un proceso de aprendizaje motor tanto en sujetos asintomáticos, como en población clínica.

En segundo lugar, el entrenamiento de OA, junto a la práctica real de ejercicios sobre la región lumbo-pélvica, condujo a un proceso de aprendizaje motor más rápido en comparación con una intervención placebo. Sin embargo, por el momento no es posible afirmar que el entrenamiento de OA cause un aprendizaje de gestos motores complejos más rápido que la IM si ambos métodos se combinan con el mismo entrenamiento real.

En tercer lugar, tanto la IM como la OA, de manera aislada, provocaron un mayor aprendizaje motor en comparación con una intervención placebo en pacientes con dolor de cuello crónico y además, el entrenamiento de OA provocó los mayores efectos.

En cuarto lugar, tanto la IM como la OA, de manera aislada, provocaron un mayor aprendizaje motor de tareas motoras manuales en comparación con una intervención placebo y además, el entrenamiento de OA provocó los mayores efectos siendo superior a la IM hasta al menos 4 meses después de la intervención, con respecto a gestos manuales de menor complejidad, y hasta al menos 1 mes en gestos manuales de mayor complejidad.

En quinto lugar, los hallazgos sugieren que el entrenamiento de OA es una herramienta más eficiente que la IM en la generación de representaciones mnémicas de los movimientos como prerrequisito al aprendizaje, y a su vez, es menos demandante, en términos de carga cognitiva, haciéndola más robusta y menos susceptible a la influencia de las variables relacionadas con la representación de movimiento.

Por último, el entrenamiento de OA parece mostrar más beneficios en pacientes postquirúrgicos, mientras que la IM parece funcionar mejor en los individuos sanos que se someten a inmovilización experimental y en las lesiones que no requieren cirugía.

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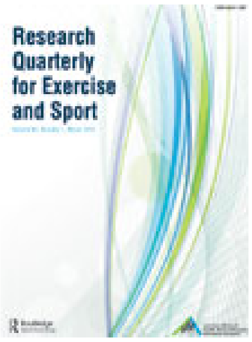
ANEXOS

Publicaciones y Estudios Originales



Research Quarterly for Exercise and Sport

ISSN: 0270-1367 (Print) 2168-3824 (Online) Journal homepage: https://www.tandfonline.com/loi/urqe20

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To cite this article: Ferran Cuenca-Martínez, Luis Suso-Martí, Daniel Sánchez-Martín, Clara Soria-Soria, Juan Serrano-Santos, Alba Paris-Alemany, Roy La Touche & Jose Vicente León-Hernández (2019): Effects of Motor Imagery and Action Observation on Lumbo-pelvic Motor Control, Trunk Muscles Strength and Level of Perceived Fatigue: A Randomized Controlled Trial, Research Quarterly for Exercise and Sport, DOI: 10.1080/02701367.2019.1645941

To link to this article: https://doi.org/10.1080/02701367.2019.1645941

Published online: 18 Oct 2019.

RESEARCH QUARTERLY FOR EXERCISE AND SPORT
https://doi.org/10.1080/02701367.2019.1645941

Effects of Motor Imagery and Action Observation on Lumbo-pelvic Motor Control, Trunk Muscles Strength and Level of Perceived Fatigue: A Randomized Controlled Trial

Ferran Cuenca-Martínez [a], Luis Suso-Martí [a,b], Daniel Sánchez-Martín[a], Clara Soria-Soria[a], Juan Serrano-Santos[a], Alba Paris-Alemany [a,c,d], Roy La Touche [a,c,d], and Jose Vicente León-Hernández [a]

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ABSTRACT

Purpose: The aim of the study was to evaluate the effects of motor imagery (MI) and action observation (AO) combined with a motor control exercises program for the lumbopelvic region. **Method**: Forty-five asymptomatic individuals were randomized into three groups: MI ($n = 15$), AO ($n = 15$) or control group (CG) ($n = 15$). The outcome measures included lumbopelvic motor control measured with a stabilizer pressure biofeedback, trunk muscle strength using a dynamometer and the perceived fatigue using a visual analogue scale. Participants were assessed at pre-intervention, at first week of intervention (mid) and post-intervention. **Results**: Regarding lumbopelvic motor control, we observed significant within-group differences between pre- and the mid and post-intervention assessment in AO group ($p < .001$, $d > 0.80$). MI and CG groups showed significant differences between pre- and post-intervention assessment ($p < .05$, $d > 0.80$). Regarding the direct comparison in the ΔMid-Pre differences between groups, only the AO group was superior to the CG with a large effect size ($d > 0.80$). Regarding trunk muscle strength, significant within-group differences between pre- and post-intervention assessments were observed in AO ($p < .001$, $d = —1.25$) and MI ($p < .05$, $d = —1.00$) groups. In relation to the perceived fatigue, statistically significant within-group differences were found in all groups ($p < .05$, $d > 0.60$). **Conclusion**: AO training caused faster changes in lumbopelvic motor control compared with the CG group. The AO strategy could be used as a guideline for teaching lumbopelvic motor control exercises.

ARTICLE HISTORY
Received 6 April 2019
Accepted 15 July 2019

KEYWORDS
Motor imagery; action observation; lumbar motor control; trunk muscle strength

Motor imagery (MI) is defined as a dynamic mental process of an action, without its actual motor execution (Decety, 1996). Action observation (AO) evokes an internal, real-time motor simulation of the movements that the observer perceives visually (Buccino, 2014). MI and AO have been shown to produce a neurophysiological activation of the brain areas related to the planning and execution of voluntary movement in a similar manner to the real action (Taube et al., 2015).

Both MI and AO trigger the activation of the neurocognitive mechanisms that underlie the planning and execution of voluntary movements in a manner that resembles how the action is performed in a real manner (Wright, Williams, & Holmes, 2014). However, this brain activity is greater during the actual execution of the movement in comparison with the mental practice. In relation to this, Miller et al. (2010) found that the magnitude of imagery-induced cortical activity change was approximately 25% of that associated with actual movement. Apart from that, a fMRI conjunction analysis revealed overlapping activation for both MI and AO training in primary motor cortex, premotor cortex, supplementary motor area, intraparietal sulcus, cerebellar hemispheres, and some parts of the basal ganglia (Munzert, Zentgraf, Stark, & Vaitl, 2008). In addition, Munzert et al. (2008) also found stronger activation for MI in the posterior insula and the anterior cingulate gyrus. However, the hippocampus, the superior parietal lobe, and the cerebellar areas were differentially activated in the AO condition.

MI and AO enable the practice of movements without the need to physically perform them and have therefore been widely used for training technical skills in athletes and musicians and in neurorehabilitation and might even play a role in motor learning and improving motor performance (Mulder, 2007). MI is recognized as one of the most popular and effective forms of training for improving learning strategies and

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has a positive effect on the acquisition of new motor skills (Anwar, Tomi, & Ito, 2011). MI also increases the capacity to perfect sports movements, as has been observed in rhythmic gymnasts (Battaglia et al., 2014).

The inclusion of MI training in a movement increases muscle activation and improves movement performance and isometric force performance (Di Rienzo et al., 2015). Combined MI and motor control exercises (MCE) have produced statistically significant changes in sensorimotor function variables of the craniocervical region and in the subjective perception of fatigue compared with MCE in isolation (Hidalgo-Peréz et al., 2015).

AO is considered a novel rehabilitation approach that effectively facilitates motor learning and serves as a therapeutic tool for neurological diseases (Agosta et al., 2017). Porro, Facchin, Fusi, Dri, and Fadiga (2007) have shown that motor performance can be facilitated even with the observation of simple movements and that AO can lead to improved motor performance and enhanced muscle strength.

Several studies have shown that therapeutic exercise improves lumbopelvic motor control, trunk muscle strength and perceived fatigue on the lumbar spine (Santos, Chiavegato, Valentim, Da Silva, & Padula, 2016; Stevens et al., 2007). MCE in the lumbopelvic region is based on the activation of the deep trunk muscles and targets the restoration of control and coordination of these muscles, progressing to more complex and functional tasks integrating the activation of deep and global trunk muscles (New, Dannaway, New, & New, 2017). MCE is commonly employed for managing patients with persistent low back pain, in which a lack of spinal stability is one of the proposed mechanisms for the onset and/or persistence of pain (New et al., 2017).

The authors hypothesized that a combination of MCE with MI or AO could result in greater improvements in lumbopelvic motor control, trunk muscle strength and perceived fatigue of the lumbar spine than an MCE program in isolation. The main objective of the present study was therefore to evaluate the effects of MI and AO combined with an MCE program on lumbopelvic motor control in the lumbar spine. The secondary objective was to assess the influence of MI and AO training combined with an MCE program on trunk muscle strength and perceived fatigue in the lumbar region in asymptomatic individuals.

Methods

Study design

This study was a single-blind, randomized controlled trial. The researcher responsible for the study outcomes was blinded to the intervention group. In addition, an independent blind assessor performed the measurements and recorded the data, and the participants were asked not to make any comments to the researcher performing the measurements. The study was planned and conducted in accordance with Consolidated Standards of Reporting Trials (CONSORT) requirements and approved by the ethics committee (CSEULS-PI-019/2019). This study was registered in the United States Randomized Trials Register on clinicaltrial.gov (trial registry number: NCT03902847).

Participant recruitment

A sample of 45 asymptomatic volunteers was recruited from the local community through social media and email. Participants were recruited between February and December 2018. The inclusion criteria were (a) asymptomatic individuals and (b) men and women aged 18 to 65 years. The exclusion criteria were (a) any knowledge of physical therapy or occupational therapy, (b) age <18 years, (c) any symptoms in the lumbopelvic region at the time of the study, (d) lumbopelvic pain within the past 6 months, (e) treatment for lumbopelvic pain in the past 6 months and (f) any type of neurological disease. All data were collected at the La Salle University Center for Advanced Studies. Informed written consent was obtained from all participants prior to inclusion. All participants were given an explanation of the study procedures, which were planned under the ethical standards of the Declaration of Helsinki.

Randomization

We randomized the participants using a computer-generated random sequence table with a balanced three-block design (GraphPad Software, Inc., CA). An independent researcher generated the randomization list, and a research team member who was not involved in assessing or treating the participants was in charge of randomizing and maintaining the list. The included participants were randomly assigned to 1 of the 3 groups using the random-sequence list, ensuring concealed allocation.

Interventions

Motor control exercises

The participants in the control group (CG) underwent an intensive training program of stabilization exercises of the lumbopelvic region. The MCE protocol consisted of 6 exercises aimed at re-educating the musculature of the lumbar region, with special attention to the contraction of the transverse and multifidus muscle (Appendix 1). The participants were asked to perform three sets of exercises of 12 repetitions each with a rest period of 1 minute between them, with a total duration of approximately 30–35 minutes. Those in the MCE program had to perform this protocol once a day, 6 days a week, for 3 weeks. All the sessions were supervised by a therapist to guide the participants in the correct performance of the exercises (Figure 1).

Motor control exercises combined with motor imagery

All participants in the MI group were informed of the procedure at the beginning of the intervention. During the first phase of the intervention (the first week), all participants had to perform the same MCE program as the CG. Unlike the CG, the MI group performed mental practice tasks based on kinesthetic mental MI in first-person perspective prior to the MCE program. Through kinesthetic MI, the participants had to imagine themselves performing each motor control exercise and feel each of the performed motor gestures, thus involving the somatosensory system. The MI group thereby imagined themselves feeling their body's position, the floor's support, the movements and the requested postures. All participants had to imagine that they were performing each exercise for 1 set of 12 repetitions prior to the actual execution of the exercise.

During the second phase (the second and third week), a question-and-answer session was conducted regarding the mental practice tasks the participants had to perform during this phase. Subsequently, the participants had to carry out the same program as the first phase. It is therefore that all participants had to imagine, in first-person perspective and in kinesthetic way, that they were performing each exercise for 1 set of 12 repetitions prior to the actual execution of each exercise (Figure 1).

Motor control exercises combined with action observation

All participants in the AO group were informed of the procedure at the beginning of the intervention. During the first phase (the first week), all participants had to perform the same MCE program as the CG. Unlike the CG, however, the AO group watched a series of 1-min videos for each exercise shown in third-person perspective prior to the actual execution of each exercise. It is therefore that all participants in the AO group watched a person perform each exercise for 1 set of 12 repetitions prior to the actual execution of each exercise.

During the second phase (the second and third week), the participants performed the same sequence as in the previous phase (Figure 1).

Procedure

After providing their informed consent to participate in the study and before starting the intervention, all participants were supplied with a set of self-report

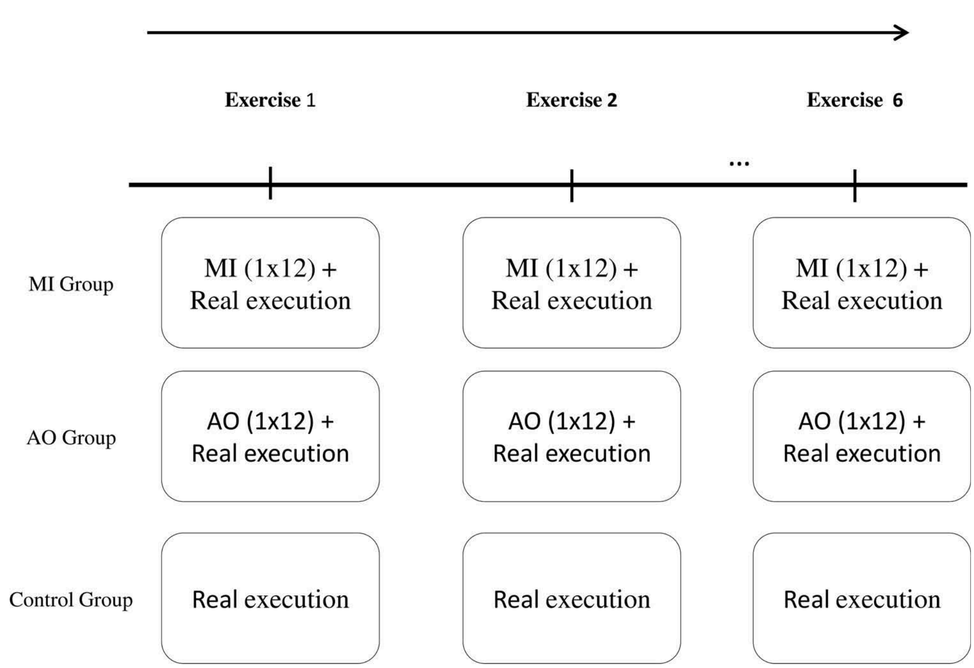

Figure 1. The protocol of the intervention.

questionnaires to verify that the participants had similar levels of physical activity and psychological conditions. The participants were assessed on 3 occasions: prior to the study (pre-intervention), after the first week (mid-intervention) and 3 weeks after the start of the intervention program (post-intervention). The measurements included an assessment of (a) lumbopelvic motor control, (b) trunk muscle strength and (c) perceived fatigue.

Self-reported outcomes

After consenting to the study, the participants were given a battery of questionnaires to complete on the day of the first assessment. The questionnaires included various self-reports for sociodemographic and psychological variables, information about sex, age, educational level and employment status, as well as the validated Spanish versions of the Tampa Scale of Kinesiophobia (TSK-11), the International Physical Activity Questionnaire (IPAQ), the Movement Imagery Questionnaire-Revised (MIQ-R) and the Self-efficacy Scale for Physical Activity (EAF).

Fear of movement

Fear of movement was assessed using the 11-item Spanish version of the TSK-11, whose reliability and validity have been demonstrated (Gómez-Pérez, López-Martínez, & Ruiz-Párraga, 2011). The TSK-11 consists of 2 subscales, one related to fear of activity and the other related to fear of harm. The final score ranges from 11 to 44 points, with higher scores indicating greater perceived kinesiophobia (Gómez-Pérez et al., 2011).

The level of physical activity

The level of physical activity was objectified through the IPAQ questionnaire, which allows the participants to be divided into 3 groups according to their level of activity, which can be high, moderate and low or inactive (Roman-Viñas et al., 2010). Given that this questionnaire has shown acceptable validity in studies measuring total physical activity, we employed the questionnaire's psychometric properties in our study.

Visual and kinesthetic motor imagery ability

The MIQ-R is an 8-item self-report inventory that assesses visual and kinesthetic motor imagery ability. Four different movements are included in MIQ-R, which is comprised of 4 visual and 4 kinesthetic items. For each item, the participants read a description of the movement, physically perform the movement and are then instructed to reassume the starting position after finishing the movement and before performing the mental task, imaging the movement visually or kinesthetically. Each participant then rates the ease or difficulty of generating that image on a 7-point scale in which 7 indicates "very easy to see/feel" and 1 "very difficult to see/feel". The internal consistencies of the MIQ-R have been consistently adequate, with Cronbach's α coefficients above 0.84 for the total scale, 0.80 for the visual subscale and 0.84 for the kinesthetic subscale (Campos & González, 2010).

Self-efficacy for physical activity

Perceived self-efficacy is defined as the person's belief in their own ability to perform a behavior that enables them to achieve certain results. Standardized tests for estimating a participants belief in their personal ability to conduct regular physical activity (self-efficacy for physical activity) helps make predictions on the actual practice of this behavior. The EAF scale has adequate content validity and high reliability (Cronbach $\alpha > 0.9$ for all factors and β of 0.96) and is appropriate for measuring the efficacy of adult users of health services in practicing regular physical activity (Fernández Cabrera, Medina Anzano, Herrera Sánchez, Rueda Méndez, & Fernández Del Olmo, 2011).

Outcome measures

Primary outcomes

Lumbopelvic motor control. Motor control of the lumbar region was evaluated with a stabilizer pressure biofeedback unit (Chattanooga Group Inc., Chattanooga, TN). Pressure biofeedback units have been employed in clinical practice to provide biofeedback during specific muscle contraction retraining and lumbopelvic stabilization exercises. These units can detect lumbopelvic movement during lower limb movements and assist in retraining movement patterns. The units are a useful tool for indicating deep abdominal function and reliably measuring lumbopelvic motor control (Cairns, Harrison, & Wright, 2000). We employed a modification of the neutral position test (developed by Azevedo et al. (2013)) based on the stabilizer instructions; the measurement was based on a protocol validated in a previous study and presents an intraclass correlation coefficient of 0.94 (95% confidence interval [CI] 0.87–0.97) (Azevedo et al., 2013). The participants were positioned in supine decubitus with the stabilizer in the lumbar region with an initial pressure of 40 mm Hg and a knee flexion of 90º. The participants were then instructed to perform a 90º hip and knee flexion with one limb and then the same action with the opposite limb. According to the stabilizer's treatment protocol, the pressure will increase between 8 and 10 mm Hg during the exercise. The evaluator performed 3 measurements and calculated the total mean pressure.

Secondary outcomes

Trunk muscle strength. Trunk muscle strength was assessed using a portable traction dynamometer (Takei Kiki Kogyo), which provided valid assessments of back and leg strength. Although evaluators need to undergo a familiarization session to reliably measure back strength, the portable dynamometer has sufficient reliability and validity to justify its use for measuring back and leg strength (Coldwells, Atkinson, & Reilly, 1994). Participants were placed on the dynamometer platform, with the knees extended and a hip flexed. Participants then held the device with their hands; a reverse grip was employed to measure back strength to deter the use of shoulder muscles during the "pull". Participants were also instructed to keep the head up during measurements, and the chain was adjusted (Coldwells et al., 1994). After the training, the participants performed a lumbopelvic extension twice while the evaluator verified that the participants had not compensated with the arm. The mean score of 2 measurements was then calculated.

Perceived fatigue. We employed the visual analogue scale of fatigue (VAS-f) to quantify the participants' perceived fatigue after performing the training session. The VAS-f uses a numerical scale of 0–10, with 0 representing minimum fatigue (no fatigue) and 10 representing maximum fatigue. The VAS-f scale is useful, sensitive and easy to apply (Lee, Hicks, & Nino-Murcia, 1991).

Statistical analysis

For the statistical analysis, we employed the Statistical Package for Social Sciences (SPSS 22, SPSS Inc., Chicago, IL, USA) and evaluated the normality of the variables using the Shapiro-Wilk test. To summarize the data for continuous variables, we employed descriptive statistics and presented the results as mean±standard deviation, 95% CI. The categorical variables are presented as absolute (number) and relative frequencies (percentage). To compare the categorical variables, we employed a chi-squared test with residual analysis. To compare the continuous outcome variables, we employed a 2-way repeated-measures analysis of variance (ANOVA). The analyzed factors were the groups (MI, AO and CG) and times. We also analyzed the time*group interaction, which is the hypothesis of interest and also the direct comparison of the differences between pre- and mid-intervention among groups (ΔAO at mid vs. ΔMI at mid vs. ΔCG). Finally, an inferential analysis of the data with a mixed multivariate analysis of variance (MANOVA) was conducted with the following covariables: IPAQ and age.

Multiple comparison techniques were requested using the Bonferroni correction. We evaluated the assumption of homoscedasticity using a Levene test and it was assumed in each variable. We also calculated the partial eta-squared (η^2_p) as a measure of the effect size (strength of association) for each main effect and interaction in the ANOVAs (0.01–0.059 represented a small effect; 0.06–0.139 represented a medium effect; and > 0.14 represented a large effect). We performed a *post hoc* analysis with Bonferroni correction in the case of significant ANOVA findings for multiple comparisons between variables. We calculated effect sizes (d) according to Cohen's method, in which the magnitude of the effect was classified as small (0.20–0.49), medium (0.50–0.79) or large (0.8). The α level was set at 0.05 for all tests.

Results

A total of 45 asymptomatic participants were included in this study and were randomly allocated to 3 groups of 15 participants per group. There were no adverse events reported in either group. No statistically significant differences in demographic data were present between the groups (Table 1) and the self-reported variables (Table 2) prior to the intervention.

Primary outcomes

Right lumbopelvic motor control

The ANOVA revealed significant changes in right lumbopelvic motor control during the group*time (*F*

Table 1. Summary of demographic variables.

Measure	CG (n = 15)	MI (n = 15)	AO (n = 15)	p-Value
Age (Years)	27.40 ± 11.20	30.15 ± 13.24	33.30 ± 15.28	0.382
Gender				0.901
Male	5 (33.3)	5 (33.3)	4 (26.7)	
Female	10 (66.7)	10 (66.7)	11 (73.3)	
Studies				0.696
Primary	2 (13.3)	1 (6.7)	1 (6.7)	
Secondary	4 (26.7)	5 (33.3)	5 (33.3)	
Superior Studies	9 (60)	9 (60)	9 (60)	
Employment situation				0.350
Active work	7 (46.7)	9 (60)	12 (80)	
Unemployment	6 (40)	5 (33.3)	2 (13.3)	
Sick Leave	0 (0)	0 (0)	0 (0)	
Retirement	2 (13.3)	1 (6.7)	1 (6.7)	

MI: Motor imagery; AO: Action observation; CG: Control group. Values are mean ± SD and n (%).

Table 2. Summary of psychological and self-reported variables.

Measure	CG (n = 15)	MI (n = 15)	AO (n = 15)	p-Value
MIQ-K	26.06 ± 2.98	25.13 ± 2.89	25.66 ± 3.13	0.697
MIQ-V	25.33 ± 3.90	24.73 ± 3.47	25.86 ± 3.60	0.700
MIQ-T	51.40 ± 6.57	49.86 ± 6.12	51.53 ± 5.59	0.711
TSK-T	23.46 ± 5.42	21.80 ± 5.07	22.13 ± 4.96	0.648
IPAQ-T (METs)	2422.30 ± 1594.09	1492.53 ± 746.60	2449.70 ± 2018.9	0.168
EAF-E	140.06 ± 34.96	165.60 ± 36.22	147.06 ± 33.32	0.129
EAF-A	83.53 ± 23.76	97.46 ± 19.71	91.46 ± 16.27	0.177
EAF-C	24.66 ± 6.56	27.20 ± 4.32	26.01 ± 8.34	0.581
EAF-T	248.26 ± 50.26	290.26 ± 50.31	264.53 ± 44.42	0.068
IPAQ				0.188
Slow	0 (0)	0 (0)	0 (0)	
Moderate	11 (73.3)	14 (93.3)	10 (66.7)	
Vigorous	4 (26.7)	1 (6.7)	5 (33.3)	

MI: Motor imagery; AO: Action observation; CG: Control group; TSK: Tampa Scale of Kinesiophobia; IPAQ: International Physical Activity Questionnaire; METS: METs are multiples of the resting metabolic rate. Values are mean ± SD and n (%).

= 2.52, $p = .047$, $\eta_p^2 = 0.107$) and time ($F = 42.90$, $p < .001$, $\eta_p^2 = 0.505$). The ANOVA revealed no significant changes in right lumbopelvic motor control during time*IPAQ ($F = 0.517$, $p = .598$, $\eta_p^2 = 0.012$). In addition, the ANOVA also revealed no significant changes in right lumbopelvic motor control during time*age ($F = 3.05$, $p = .056$, $\eta_p^2 = 0.06$). The *post hoc* analysis revealed significant intragroup differences. We observed statistically significant differences between the pre-intervention, mid-intervention and post-intervention assessments only in the AO group, with a large effect size ($p < .001$, $d = 1.31$ and $p < .001$, $d = 2.12$ respectively). Both the MI and CG groups showed significant differences only between the pre-intervention and post-intervention assessments, with a large effect size ($p < .001$, $d = 1.08$ and $p < .05$, $d = 1.05$ respectively) (Table 3).

In addition, we directly compare differences between pre- and mid-intervention among groups (ΔAO at mid vs. ΔMI at mid vs. ΔCG). The ANOVA revealed significant changes in right lumbopelvic motor control ($F = 3.58$, $p = .037$). The AO group showed significant between groups differences with the CG with a large effect size ($p = .036$, $d = 0.94$). However, the AO group showed no significant between groups differences with the MI group ($p = .255$) (Figure 2).

Left lumbopelvic motor control

The ANOVA revealed significant changes in left lumbopelvic motor control during the group*time ($F = 2.66$, $p = .046$, $\eta_p^2 = 0.113$) and time ($F = 37.09$, $p < .001$, $\eta_p^2 = 0.469$). The ANOVA revealed no significant changes in left lumbopelvic motor control during time*IPAQ ($F = 1.33$, $p = .268$, $\eta_p^2 = 0.03$). In addition, the ANOVA also revealed no significant changes in left lumbopelvic motor control during time*age ($F = 0.32$, $p = .698$, $\eta_p^2 = 0.008$). The *post hoc* analysis revealed significant intragroup differences. We observed statistically significant differences between the pre-intervention, mid-intervention and post-intervention assessments only in the AO group, with a large effect size ($p < .001$, $d = 1.03$ and $p < .001$, $d = 1.36$ respectively). Both the MI and CG groups showed significant differences only between the pre-intervention and post-intervention assessments, with a large effect size ($p < .001$, $d = 0.95$ and $p < .05$, $d = 1.39$ respectively) (Table 3).

In addition, we directly compare differences between pre- and mid-intervention among groups (ΔAO at mid vs. ΔMI at mid vs. ΔCG). The ANOVA revealed significant changes in left lumbopelvic motor control ($F = 4.08$, $p = .024$). The AO group showed significant between groups differences with the CG with a large effect size ($p = .03$, $d = 0.93$). However, the AO group showed no significant between groups differences with the MI group ($p = .107$) (Figure 2).

Secondary outcomes

Trunk muscle strength

The ANOVA revealed significant changes in trunk muscle strength over time ($F = 14.86$, $p < .01$, $\eta_p^2 = 0.261$). The ANOVA revealed no significant changes in trunk muscle strength during time*IPAQ ($F = 2.89$, $p = .068$, $\eta_p^2 = 0.06$). In addition, the ANOVA also revealed no significant changes in trunk muscle strength during time*age ($F = 0.19$, $p = .827$, $\eta_p^2 = 0.005$). The *post hoc* analysis revealed statistically significant intragroup differences between the pre-intervention and the post-intervention assessment, with a large effect size in the AO ($p < .001$, $d = -1.25$) and MI ($p < .05$, $d = -1.00$) groups. We observed no significant intragroup differences in the CG ($p \geq 0.05$) (Table 4).

Table 3. Results of primary outcomes.

Measure	Group	Mean ± SD Pre	Mid	Post	Mean difference (95%CI); Effect size (d) a) pre – mid b) pre – post
	CG	54.06±5.49	52.03±6.11	48.40±5.22	a) 2.03 (-2. 31 to 6.19); d= 0.35 b) 5.67* (1.77 to 9.56); d= 1.05
LMC-R (mmHg)	MI	55.00±7.83	50.93±8.17	47.33±6.23	a) 4.06 (-.09 to 8.23); d= 0.50 b) 7.66** (3.77 to 11.56); d= 1.08
	AO	58.01±6.36	49.76±6.16	46.86±3.85	a) 8.23** (4.07 to 12.39); d= 1.31 b) 11.13** (7.23 to 15.03); d= 2.12
Mean difference (95%CI) Effect size (*d*)					
MI-AO		-3.00 (-9.05 to 3.04); d= -0.42	1.16 (-5.10 to 7.43); d= 0.16	.46 (-4.26 to 5.19) d= 0.09	
MI-CG		.93 (-5.11 to 6.97) d= 0.14	-1.10 (-7.36 to 5.16), d= -0.15	-1.06 (-5.79 to 3.66); d= -0.18	
AO-CG		3.93 (-2.11 to 9.97); d= 0.66	-2.26 (-8.53 to 4.01); d= -0.37	-1.53 (-6.26 to 3.19); d= -0.33	
	CG	53.86±4.65	52.43±5.90	47.33±5.19	a) 1.43 (-3.12 to 5.98); d=0 .27 b) 6.53* (2.40 to 10.66); d= 1.39
LMC-L (mmHg)	MI	55.13±7.72	52.33±8.34	48.10±7.04	a) 2.80 (-1.75 to 7.35); d= 0.34 b) 7.03** (2.90 to 11.16); d= 0.95
	AO	56.66±9.80	48.26±6.05	46.30±4.90	a) 8.40** (3.84 to 12.95); d= 1.03 b) 10.36** (6.23 to 14.45); d= 1.36
Mean difference (95%CI) Effect size (d)					
MI-AO		-1.53 (-8.53 to 5.47); d= -0.17	4.06 (-2.18 to 10.31); d= 0.56	1.80 (-3.47 to 7.07) d= 0.30	
MI-CG		1.26 (-5.73 to 8.27) d= 0.20	-.10 (-6.34 to 6.14), d= -0.01	.76 (-4.50 to 6.04); d= 0.12	
AO-CG		2.80 (-4.20 to 9.80); d= 0.36	-4.16 (-10.41 to 2.08); d= -0.70	-1.03 (-6.30 to 4.23); d= -0.19	

*p < 0.05; **p < 0.01; LMC: Lumbo-pelvic Motor Control; mmHg: Millimetres of Mercury; CG: Control Group; MI: Motor Imagery; AO: Action Observation

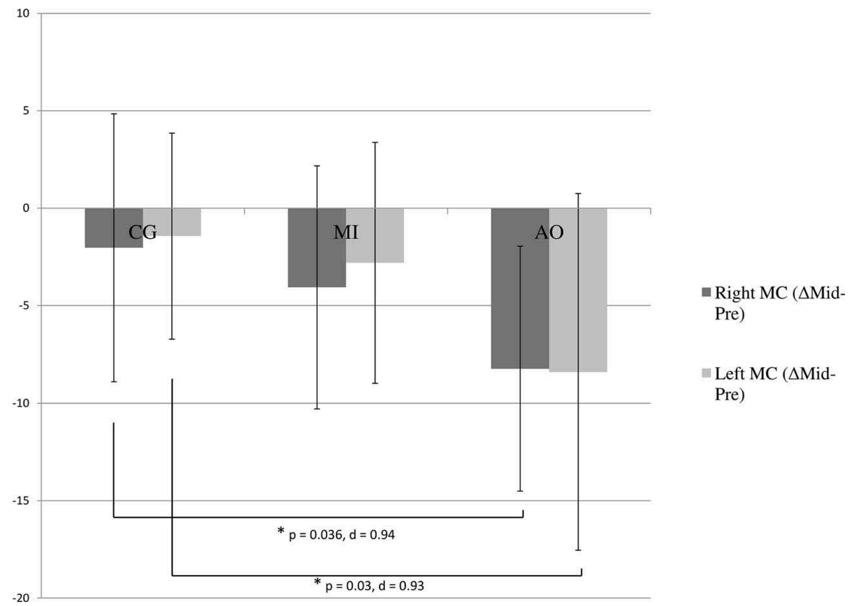

Figure 2. ΔMid-pre between groups comparison (MC: Motor Control, MI: Motor Imagery, AO: Action Observation, CG: Control Group).

Perceived fatigue

The ANOVA revealed significant changes in VAS-f over time (F = 47.34, $p < .001$, $\eta_p^2 = 0.530$). The ANOVA revealed no significant changes in perceived fatigue during time*IPAQ (F = 0.142, p = .867, $\eta_p^2 = 0.002$). In addition, the ANOVA also revealed no significant changes in perceived fatigue during time*age (F = 2.32, p = .114, $\eta_p^2 = 0.054$). The analysis revealed statistically significant intragroup differences in the 3 groups between the pre-intervention, mid-intervention and post-intervention assessments, with a moderate to large effect size ($p < .05$, $d > 0.60$) (Table 4).

Discussion

The aim of this study was to compare the effect of MI and AO along with physical training in improving lumbopelvic motor control, trunk muscle strength and perceived fatigue. Our results suggest that the MCE-AO group experienced faster changes than the MCE group in lumbopelvic motor control. With regard to the secondary outcomes, only the MI and AO groups showed intragroup significant changes in increased trunk muscle strength; however, there were no differences between the three groups in terms of perceived fatigue.

The results show that the three intervention groups achieved significant improvements in motor control between the pre-intervention and post-intervention measurements; however, only the group that performed the MCE-AO achieved improvements in the mid-intervention measurement.

Motor control is a complex process that involves not only its execution but also the correct planning and programming of the movement, as well as the adjustment of the tone, strength and synchronization of the various organs affecting the movement (Latash, Levin, Scholz, & Schöner, 2010).

Given the relevance of this process and our increasing knowledge of the nervous system, a large volume of research has been conducted into the learning process for these movements and the optimization of motor learning, both from the context of sports science and rehabilitation. Although there are several current theories on the neurophysiological processes involved in motor learning (Doyon & Benali, 2005), these theories agree that when an individual learns a new motor task, a neuroplasticity process occurs during the phases of acquisition, consolidation and automation or retention of the task (Dayan & Cohen, 2011). As evidenced by our results, practicing a task is unquestionably a fundamental aspect in acquiring and consolidating a motor task, both for the intrinsic improvement of the skill and for stabilizing the procedural memory (Robertson, Pascual-Leone, & Miall, 2004).

The mental practice of motor gestures produces cortical representations and neural substrates similar to those produced by real practice, making MI and AO relevant motor learning strategies (Ehrsson, Geyer, & Naito, 2003; Naish, Houston-Price, Bremner, & Holmes, 2014). However, the results of the present study show that only the MCE-AO group achieved significant differences in the mid-intervention measurement, results that are consistent with current

Table 4. Results of secondary outcomes.

Measure	Group	Mean ± SD Pre	Mid	Post	Mean difference (95%CI); Effect size (d) a) pre – mid b) pre – post
	CG	3.83±2.26	2.40±1.50	1.46± .83	a) 1.43* (.36 to 2.49); d= 0.74 b) 2.36** (1.18 to 3.54); d= 1.40
VAS-f	MI	4.66±1.79	3.20±1.14	2.13±1.50	a) 1.46* (.40 to 2.53); d= 0.97 b) 2.53** (1.35 to 3.71); d= 1.53
	AO	3.46±2.29	2.33±1.39	1.53±1.06	a) 1.13* (.06 to 2.19); d= 0.60 b) 1.93** (.75 to 3.11); d= 1.08
Mean difference (95%CI) Effect size (d)					
MI-AO		1.20 (-.74 to 3.14); d= 0.58	.86 (-.37 to 2.10); d= 0.68	.60 (-.46 to 1.66) d= 0.46	
MI-CG		.83 (-1.10 to 2.77) d= 0.40	.80 (-.43 to 2.03), d= 0.60	.66 (-.39 to 1.73); d= 0.55	
AO-CG		-.36 (-2.30 to 1.57); d= -0.16	-.06 (-1.30 to 1.17); d= -0.04	-.06 (-.99 to 1.12); d= 0.07	
	CG	30.05±15.17	31.03±16.75	37.06±17.06	a) -.98 (-8.07 to 6.10); d= -0.06 b) -7.01 (-14.47 to .44); d= -0.43
TMS (Kg)	MI	31.46±9.58	35.50±13.98	39.99±7.28	a) -4.03 (-11.12 to 3.05); d= -0.33 b) -8.53* (-15.94 to -1.07); d= -1.00
	AO	27.45±9.46	32.93±8.72	39.20±9.34	a) -5.48 (-12.57 to 1.60); d= -0.60 b) -11.75** (-19.21 to -4.28); d= -1.25
Mean difference (95%CI) Effect size (d)					
MI-AO		4.01 (-6.64 to 14.68); d= 0.42	2.56 (-9.78 to 14.92); d= 0.22	.79 (-10.12 to 11.72) d= 0.09	
MI-CG		1.41 (-9.24 to 12.08) d= 0.11	4.46 (-7.88 to 16.82), d= 0.29	2.93 (-7.98 to 13.85); d= 0.22	
AO-CG		-2.60 (-13.26 to 8.06); d= -0.20	1.90 (-10.45 to 14.25); d= 0.14	2.13 (-8.78 to 13.05); d= 0.15	

*p < 0.05; **p < 0.01; VAS-f: Visual Analogue Scale-fatigue; TMS: Trunk Muscles Strength; Kg: Kilograms; CG: Control Group; MI: Motor Imagery; AO: Action Observation scientific literature. Frank, Land, Popp, and Schack (2014) showed that when MI is added to the actual practice of a motor gesture, MI can create cognitive adaptations and improve then mental representation compared with real practice performed exclusively. Mulder, Zijlstra, Zijlstra, and Hochstenbach (2004) however, showed that MI appears to be more effective in the motor learning of previously known gestures as opposed to totally new gestures.

Individuals who routinely perform the imagined motor gesture appear to use MI more frequently than those who perform new motor tasks (Cumming & Hall, 2002), which could be due to compression of the motor system at the cortical level. During MI, the individual who performs the mental practice depends exclusively on their own capacity to evoke the motor representation of the motor gesture. For a complex gesture such as MCE, the absence of a visual input and an adequate context appears to influence the activation of the movement planning and the programming areas responsible for motor learning.

In addition, the individual receives a visual stimulus from a model when performing the action correctly in an appropriate context, providing feedback that appears to influence the way in which the individual acquires the motor gesture, as shown by the results of this study (Mulder, 2007). These findings are consistent with those from studies by Stefan et al. (2005) and Mattar and Gribble (2005), who demonstrated the participation of the mirror neuron system in AO training and its relevance in motor memory for motor learning.

Regarding the trunk muscle strength and perceived fatigue, the results of the present study show that the MCE-AO and MCE-MI groups achieved statistically intra-group significant changes in lumbar muscle strength between the pre-intervention and post-intervention measurements; however, this change did not occur in the CG. The results are consistent with those found by Ranganathan, Siemionow, Liu, Sahgal, and Yue (2004). Cortical activation produced by AO and MI appears to increase the mental representation of the motor gesture, increasing cortical excitability and the recruitment of motor units in the production of force (Sale, MacDougall, Upton, & McComas, 1983). Performing IM or AO could lead to increased confidence and motivation to perform the strength task compared with the group that did not perform the mental practice (Cumming & Hall, 2002), which could be one of the main hypotheses for the results of this study. There is, however, a lack of scientific literature on the involvement of mental practice in perceived fatigue. The results of the present study show no differences between the groups in this variable, findings that are consistent with data from the scientific literature, which show no increases in neuromuscular fatigue after the use of MI when compared with real practice (Rozand, Lebon, Papaxanthis, & Lepers, 2014).

Our results show that AO training resulted in faster changes than the control exercises in lumbopelvic motor control. The AO strategy could therefore be employed as a tool for teaching lumbopelvic motor control exercises, at least during the early stages of neuro-sensorimotor control. In terms of the secondary endpoints, only the MI and AO groups showed significant intragroup changes in increased trunk muscle strength. Finally, there were no differences between the three groups in terms of perceived fatigue.

Limitations

The present study presents several limitations. First, the results of this research must be interpreted carefully because the study was conducted with asymptomatic participants. It is not possible to completely extrapolate the results to patients who have pain or functional disorders, in which MCE is commonly employed for rehabilitating lumbar spine disorders. Second, regarding the total time exposed to the activity assessed, both MI, and AO groups performed a higher number of repetitions due to the imagery and observation intervention itself compared to the other group. This difference could have influenced the results as the total training was longer. There is a wide literature showing better effects of MI and AO along with physical practice compared to the only physical practice. These studies also used longer intervention times for MI, as in the case of the present study (Hidalgo-Peréz et al., 2015; Kumar, Chakrapani, & Kedambadi, 2016; Losana-Ferrer, Manzanas-López, Cuenca-Martínez, Paris-Alemany, & La Touche, 2018). Third, the results were only measured in the short term, and the medium-term and long-term impact of the interventions need to be evaluated. It would have been interesting if the MCE had progressed to more advanced phases in which additional loads, common exercises of daily life, and functional and more complex movement patterns were included. Finally, the International Physical Activity Questionnaire in the MI was relatively smaller than two other groups. Although these differences were not statistically significant, the authors believe that this value should be taken into consideration.

What does this article add?

The results of the present study show that including AO can affect the learning of complex motor gestures such as those performed in MCE. The use of AO together with the real practice of the motor gesture could lead to faster learning of this gesture, which should be considered in the motor learning of complex motor gestures within sports practice. MCE are exercises widely used in the field of rehabilitation, showing positive results in reducing pain and disability in individuals with chronic low back pain. The implementation of mental practice within these rehabilitation protocols could provide a benefit in how patients physically learn these exercises and could improve the rehabilitation processes.

Our results show that implementing AO or MI led to improved lumbar region strength. Strength is one of the most relevant variables in sports practice and rehabilitation. Increased strength is related to increased sports performance and lower injury rates. Including MI or AO, along with the real practice of MCE, could therefore present benefits in increasing strength, both in asymptomatic and symptomatic individuals, as well as for their rehabilitation. Mental practice appears to be a safe and useful technique in terms of its cost-benefit. Although further research is needed for its clinical transfer to sports and rehabilitation sciences, mental practice is a technique to be considered.

Acknowledgments

We thank the Centro Superior de Estudios Universitarios (CSEU) La Salle for making this study possible, as well as all the participants in the study.

Funding

The authors received no funding for this work.

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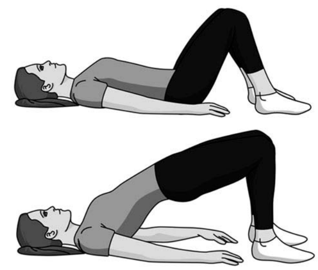
Appendix 1

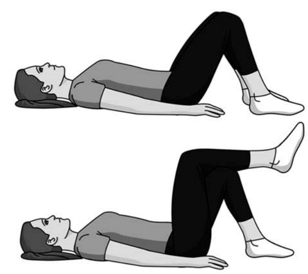
MCE exercises protocol

Exercise 1:
Static lumbopelvic stabilization. In supine crook lying position. With flexed knees and hips at 60º and 90º respectively, and neutral lumbopelvic position. The participant performed a coactivation of the abdomino-pelvic muscles (pelvic floor, transverse, and multifidus muscles contraction) during the exhalation phase of the breathing, performing an abdominal bracing maneuver maintaining the neutral lumbopelvic position.

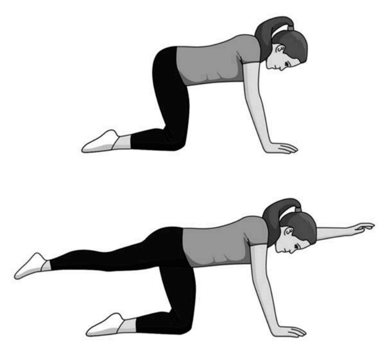
Exercise 2:
Supine bridge exercise. In supine with lumbopelvic neutral position and flat feet, the subject made an inspiration, and then performed pelvic retroversion continued by a lumbopelvic lifting motion with active lumbopelvic stabilization, during exhalation. The exercise ended at the initial position after bringing down the pelvis.



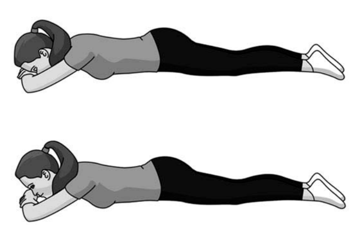
Exercise 3:
Alternate knee raises. In supine position with lumbopelvic neutral position, the subject performed an inspiration, and during the exhalation performed a 90º hip flexion with 90º knee flexion, alternating legs with each repetition. The subject had to maintain the lumbopelvic neutral position during the exercise.



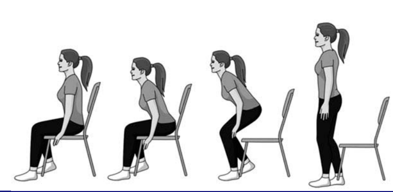
Exercise 4:
Arm and leg elevation in Quadruped position. Maintaining lumbopelvic neutral position, the subject performed an elevation of one arm and the opposite leg at the same time during the expiratory phase of the breathing, while co-activating the abdomino-pelvic muscles. Dynamic lumbopelvic stabilization was required during the exercise. Alternating arms and legs at each repetition.



Exercise 5:
Lumbar extension exercise. The subject placed in the prone position, with the forehead laying on the hands. The subject performed an elevation of the head and sternum with co-activation of the abdomino-pelvic muscles during the exhalation phase.



Exercise 6:
Standing from sitting exercise. The subject was sitting with a neutral lumbopelvic position, keeping flat feet with one of them advanced. A complete standing movement was performed maintaining lumbar stabilization, with a slight bending forward of the body. The return to sitting position was done in the same way.



Mental practice in isolation improves cervical joint position sense in patients with chronic neck pain: a randomized single-blind placebo trial

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ABSTRACT

Objective. The main objective of this trial was to assess whether action observation (AO) training and motor imagery (MI) produced changes in the cervical joint position sense (CJPS) both at the end of the intervention and 10 min postintervention compared with a placebo intervention in patients with nonspecific chronic neck pain (NSCNP).
Methods. A single-blind placebo clinical trial was designed. A total of 30 patients with NSCNP were randomly assigned to the AO group, MI group or placebo observation (PO) group. CJPS in flexion, extension and rotation movements in both planes were the main variables.
Results. The results obtained in the vertical plane showed that the AO group obtained greater improvements than the PO group in the CJPS in terms of cervical extension movement both at the end of the intervention and 10 min postintervention ($p = .001$, $d = 1.81$ and $p = .004$, $d = 1.74$, respectively), and also in cervical flexion movement, although only at 10 min after the intervention ($p = .035$, $d = 0.72$). In addition, the AO group obtained greater improvements than the MI group in the CJPS only at the end of the intervention in cervical extension movement ($p = .041$, $d = 1.17$). Regarding the left rotation cervical movement, both the MI and AO groups were superior to the PO group in both planes at the end of the intervention ($p < .05$, $d > 0.80$).
Conclusions. Although both AO and MI could be a useful strategy for CJPS improvement, the AO group showed the strongest results. The therapeutic potential of the application of mental practice in a clinical context in the early stages of rehabilitation of NSCNP should be considered.

Subjects Anesthesiology and Pain Management, Anatomy and Physiology, Global Health, Kinesiology
Keywords Action observation, Motor imagery, Joint position sense, Chronic neck pain

Submitted 25 July 2019
Accepted 16 August 2019
Published 12 September 2019

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Academic editor
Justin Keogh

Additional Information and Declarations can be found on page 18

DOI **10.7717/peerj.7681**

How to cite this article Cuenca-Martínez F, La Touche R, León-Hernández JV, Suso-Martí L. 2019. Mental practice in isolation improves cervical joint position sense in patients with chronic neck pain: a randomized single-blind placebo trial. *PeerJ* **7**:e7681 http://doi.org/10.7717/peerj.7681

INTRODUCTION

Neck pain is a common musculoskeletal disorder with a high prevalence in the population and is the fourth leading disability-generating condition (Vos et al., 2013). Chronic neck pain is often considered nonspecific (NSCNP), due to the difficulty in identifying the origin of the pain, when imaging tests provide no relevant information for establishing an accurate pathological diagnosis (Bogduk, 2011). This clinical condition is thought to have a multidimensional nature due to the combination of a complex pathogenesis, the presence of maladaptive processes of central neuroplasticity and in pain processing, as well as the relevance of psychological aspects involved in the NSCNP such as anxiety or pain catastrophism (Binder, 2007; Dimitriadis et al., 2015; Muñoz García et al., 2016).

It is commonly reported that patients with NSCNP present an alteration in the cervical joint position (Alahmari et al., 2017). The cervical region has a large number of proprioceptive receptors, especially in the upper cervical spine (Falla, Jull & Hodges, 2004; Falla, Bilenkij & Jull, 2004). It has been suggested that in patients with NSCNP, proprioceptive afferent information from the cervical spine might be impaired due to the presence of chronic pain (Uremović et al., 2007). In addition, Kim, Kim & Nabekura (2017) have suggested that patients with persistent pain might undergo a process of maladaptive neuroplasticity in major sensitive areas such as the primary somatosensory area. Furthermore, Hodges & Tucker (2011) suggested that maladaptive processes of central plasticity could lead to impaired motor planning and movement execution as a pain response and could therefore affect motor control and movement acuity in this region.

To improve proprioceptive input in the cervical region, several interventions have been proposed, including craniocervical motor control exercises (MCEs) (Izquierdo et al., 2016; Kim & Kwag II, 2016; Lee & Kim, 2016). MCEs have been shown to reduce pain and disability in patients with NSCNP compared with other types of treatments (Martin-Gomez et al., 2019). However, it has been suggested that patterns of muscle activation and recruitment are altered in the presence of pain, so implementing MCEs is a challenging aspect in these patients and might lead patients to perform them incorrectly, which could reduce their effectiveness (Sterling, Jull & Wright, 2001a). One of the alternatives in those early stages of intervention could be mental practice based on mental motor imagery (MI) and action observation (AO).

MI is defined as a dynamic mental process that involves the representation of an action, in an internal manner, without its actual motor execution (Decety, 1996). AO evokes an internal, real-time simulation of what the observer is seeing (Buccino, 2014). It has been shown that both MI and AO training can activate neurocognitive mechanisms underlying the planning and execution of voluntary movements in a similar manner as when this movement is actually performed (Wright, Williams & Holmes, 2014). Previously Villafañe et al. (2016) found an improvement in motor function through mental practice after total hip arthroplasty.

The authors hypothesize that both forms of mental practice in isolation could lead to changes in cervical joint position sense (CJPS) compared with a placebo intervention. Therefore, the main objective of the present study was to assess whether AO training and

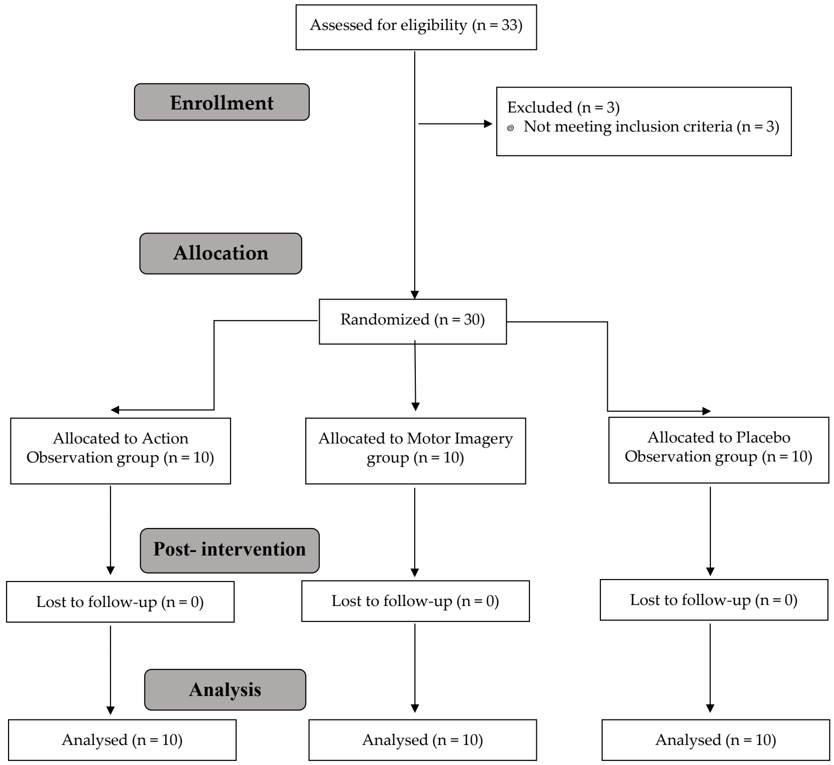

Figure 1 **Study flow chart.**

Full-size DOI: 10.7717/peerj.7681/fig-1

mental MI produced changes in CJPS both at the end of the intervention and 10 min postintervention in comparison with a placebo intervention in patients with NSCNP.

METHODS

Study design

The present study was a randomized, single-blind placebo clinical trial, planned and conducted in accordance with Consolidated Standards of Reporting Trials requirements (*Schulz et al., 2010*) (Fig. 1) and was approved by La Salle University Center for Higher Education (CSEULS-PI-027/2019).

This study was registered in the United States Randomized Trials Registry on https://www.clinicaltrials.gov/ (trial registry number: NCT03910829). All patients completed the informed consent document prior to the study.

Recruitment of participants

Patients who were diagnosed by their family doctor as having NSCNP were referred to the primary care physiotherapy service, and all met the inclusion criteria of the study at one physiotherapy center. Participants were recruited between April 2019 and May 2019.

The inclusion criteria were as follows: (a) men and women aged between 18 and 65 years; and (b) a medical diagnosis of NSCNP with at least 6 months of neck pain symptoms. Exclusion criteria were the following: (a) patients with rheumatic diseases, cervical hernia or radicular pain, cervical whiplash syndrome, neck surgeries or a history of arthrodesis; (b) systemic diseases; (c) vision, hearing or vestibular problems; and (d) severe trauma or a traffic accident that had an impact on the cervical area. All the participants were given an explanation of the study procedures, which were planned under the ethical standards of the Helsinki Declaration. In addition, this randomized, single-blind placebo clinical trial was used as a pilot with the aim of calculating the sample size of a future study.

Randomization

Randomization was performed using a computer-generated random sequence table with a non-balanced 3-block design (GraphPad Software, Inc., CA, USA). An independent researcher generated the randomization list, and a member of the research team who was not involved in the assessment or intervention of the participants was in charge of the randomization and maintained the list. Those included were randomly assigned to 1 of the 3 groups using the random-sequence list, ensuring concealed allocation.

Blinding

The assessments and treatments were performed by different therapists. The evaluator was blinded to the participant's assignment. All the intervention procedures were performed by the same physiotherapist, who had more than three years of experience in the field and was blinded to the purpose of the study. Patients were blinded to their group allocation.

Interventions

The interventions were previously described by *Suso-Martí et al. (2019)*.

Action observation group

Patients in this group performed an exclusive AO protocol of 2 commonly used MCEs in the treatment of patients with NSCNP (*Jull et al., 2009*; *Jull et al., 2007*; *O'Leary et al., 2007*). Both exercises were based on the motor gesture of craniocervical flexion (Fig. 2). Patients in the AO group performed the observation by watching a video of the continuous performance of both exercises repeatedly during 2 series of 1 min for each exercise, with a total duration of 4 min.

The first exercise consisted of maintaining the cervical spine in a neutral position in a sitting position and performing a deep muscle contraction to flatten the curve of the neck, nodding with the head. The second exercise involved a deep muscle contraction by performing the craniocervical flex-extension gesture with the resistance of an elastic band.

Motor imagery group

The patients in this group performed an MI protocol of the same cervical exercises as the AO group (Fig. 2). Patients were instructed on the movements they were to imagine by showing both exercises and the precise instructions for each movement. After this, they were instructed to perform a third-person mental task of visual MI of both exercises during 2 series of 1 min for each exercise, with a total duration of 4 min.

Placebo observation group

Patients in the placebo observation (PO) group underwent a placebo AO protocol. The patients watched during the same intervention time as both previous groups. This

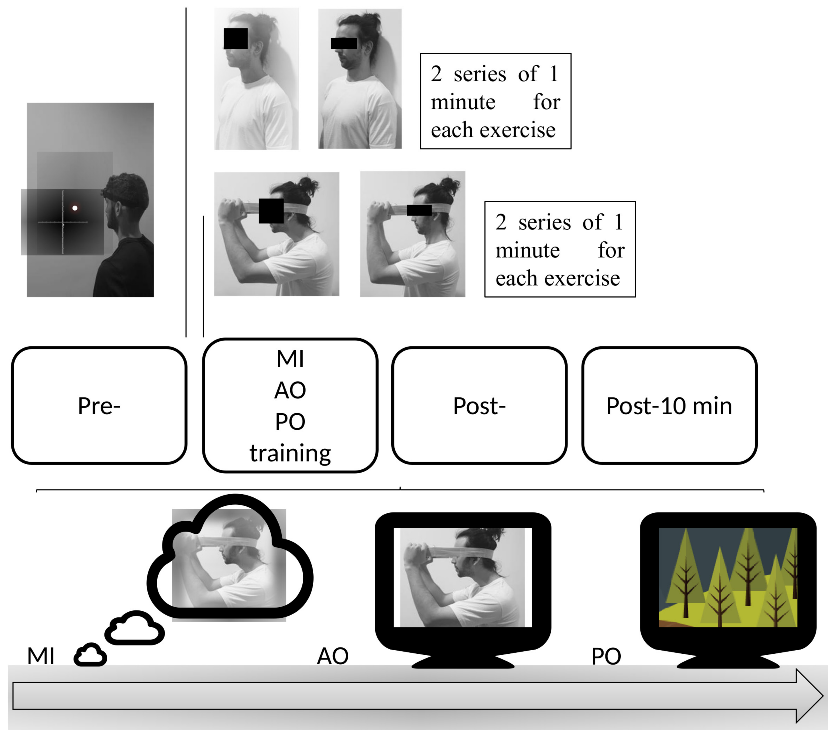

Figure 2 **Protocol of the intervention.**

Full-size DOI: 10.7717/peerj.7681/fig-2

documentary video was composed of video clips of nature landscapes, without any human agent or motor gesture.

This type of placebo AO protocol has been used in previous studies (*Bang et al., 2013*; *Buccino et al., 2012*).

Outcomes

Primary outcomes

Cervical joint position sense. CJPS is an objective measure of neck repositioning sense and can quantify the alteration in neck proprioception. CJPS was assessed with a visual feedback device, the SenMoCOR LED (Sensory Motor Control-Oriented Rehabilitation, IAOM-US). This device consists of adjustable straps and a fastening support for a laser beam. It is adjustable to the evaluator's desired position, allowing projection of the light beam.

The experimental procedure for assessing CJPS with a laser beam has been described by *Revel, Andre-Deshays & Minguet (1991)*. First, patients were asked to sit in a comfortable position at 90-cm distance from the bullseye with the SenMoCOR Kit correctly placed. With eyes closed, they were asked to point to the neutral position of the head and memorize it to return to after the completion of the movement. This point was recorded as a reference for each patient. The patient subsequently performed a maximal movement of cervical flexion and then attempted to find the initial reference position with a maximum of accuracy without speed instructions. The point on which the light beam stopped indicated the global error measured in centimeters (cm) in relation to the center of the target recorded previously. The assessor measured the deviations from de target position for each trial on both axes (x/y). Values of x (abscissa) and y (ordinate) were recorded according to the Cartesian coordinate system. The same protocol was used for the extension, right and left rotation movements. Ten trials were performed with head repositioning after each movement, and the mean measure was recorded. No feedback was given to the participants about their actual performance. This CJPS testing method offers an easy, quick and inexpensive method for measuring cervical joint position sense. The test presents inter-rater reliability ranging from moderate to good/substantial agreement (intraclass correlation coefficient [ICC] $\geq$ 0.51–0.75); it also presents intra-rater reliability ranging from moderate to almost perfect agreement (ICC $\geq$ 0.48–0.82) (*Juul et al., 2013*). The minimal detectable change ranged from 0.52–0.75 cm (*Juul et al., 2013*).

Secondary outcomes

Ability to generate mental motor imagery. The movement imagery questionnaire-revised (MIQ-R) is an 8-item self-report inventory that was used to assess visual and kinesthetic motor imagery ability. Four different movements are included in the MIQ-R, which is comprised of four visual and four kinesthetic items. For each item, participants read a description of the movement. They then physically performed the movement and were instructed to reassume the starting position after finishing the movement and before performing the mental task, imagining the movement visually or kinesthetically. Each participant then rated the ease or difficulty of mentally generating that image on a 7-point scale, in which 7 indicates "very easy to see/feel" and 1 "very difficult to see/feel". The internal consistencies of the MIQ-R have been consistently adequate, with Cronbach's α coefficients ranging above 0.84 for the total scale, 0.80 for the visual subscale and 0.84 for the kinesthetic subscale (*Campos & González, 2010*).

Mental chronometry. Mental chronometry (MC) is a reliable measure that has been widely used to record objective measurements of the ability to create mental motor images (*Guillot & Collet, 2005*; *Malouin et al., 2008*; *Williams et al., 2015*). To assess MC, first, the time dedicated to imagining each task was recorded using a stopwatch. The time between the interval command to start the task (given by the evaluator) and the verbal response at the conclusion of the task (given by the participant) was recorded. After the MI task, the participants were asked to perform the real movement execution of the task, and the time dedicated to performing each task was recorded using a stopwatch. Both time measurements were taken to obtain the temporal congruence between the tasks. In healthy participants, for the temporal congruence test, the ICC ranged from 0.63 to 0.95, whereas the ICC for intrasession reliability ranged from 0.95 to 0.97 (*Malouin et al., 2008*).

Pain-related fear of movement. Pain-related fear of movement was assessed using the 11-item Spanish version of the Tampa Scale of kinesiophobia, whose reliability and validity have been demonstrated (*Gómez-Pérez, López-Martínez & Ruiz-Párraga, 2011*). The Tampa scale for Kinesiophobia consists of 2 subscales, one related to fear of activity and the other related to fear of harm. The final score can range between 11 and 44 points, with higher scores indicating greater perceived kinesiophobia (*Gómez-Pérez, López-Martínez & Ruiz-Párraga, 2011*). Internal consistency ratings were moderate. In the chronic pain sample, Cronbach's $\alpha = 0.79$ was obtained using total TSK items (*Gómez-Pérez, López-Martínez & Ruiz-Párraga, 2011*).

Neck disability. Disability was measured using the Spanish-validated Neck Disability Index (NDI), which consists of 10 items related to daily functional activities. Each question is measured on a scale from 0 (no disability) to 5, and an overall score out of 100 is calculated by adding each item score together and multiplying it by 2. A higher NDI score indicates greater perceived disability due to neck pain. It has been shown to have high "test-retest" reliability and to have appropriate psychometric properties (*Alfonso Andrade Ortega, Damián Delgado Martínez & Almécija Ruiz, 2008*). *MacDermid et al. (2009)* concluded that differences in 7 points out of 50 in the NDI should be considered as clinically relevant. In addition, intraclass correlation coefficients (ICCs) ranged from 0.50 to 0.98.

Level of physical activity. The level of physical activity was assessed using the IPAQ questionnaire, which allows the participants to be divided into 3 groups according to their level of activity, which can be high, moderate, and low or inactive (*Roman-Viñas et al., 2010*). This questionnaire has shown acceptable validity and psychometric properties to measure total physical activity. Therefore, the psychometric properties of the questionnaire were accepted for use in studies that required the measurement of physical activity; reliability was approximately 0.65 ($r = 0.76$; 95% CI [0.73–0.77]) (*Mantilla Toloza & Gómez-Conesa, 2007*).

Procedures

Data were collected as previously described by *Suso-Martí et al. (2019)*. Each participant was given an informed consent document to participate in the study, in addition to a set of questionnaires to complete before starting the intervention. These questionnaires included psychometrics forms and a questionnaire about age, gender, time with pain duration and pain intensity. The psychological variables were evaluated with self-assessments. Then MIQ-R and mental chronometry were assessed, and the pre-intervention measurements of CJPS were then taken. Subsequently, in a sitting position, patients performed the AO, MI or PO protocol, according to their group. Immediately after the intervention, a blinded evaluator measured the CJPS in the four movements. Following this, patients were asked to sit and relax comfortably, without movement, for 10 min, and the CJPS was measured again (post 2).

Statistical analysis

The statistical analysis was performed using SPSS software version 22.0 (SPSS Inc., Chicago, IL, USA).

The normality of the variables was evaluated using the Shapiro–Wilk test. Descriptive statistics were used to summarize the data for the continuous variables and are presented as mean ± standard deviation and 95% confidence interval. A two-way repeated measures analysis of variance (ANOVA) was conducted to study the effect of the between-subject factor 'intervention group' with three categories (i.e., AO, MI and PO) and the within-subject called 'time' with also three categories (i.e., pre, post, and post 2) on the dependent variables. Partial eta squared (η_p^2) was calculated as a measure of effect size (strength of association) for each main effect and interaction in the ANOVAs, with 0.01–0.059 representing a small effect, 0.06–0.139 a medium effect and >0.14 a large effect (Cohen, 1973). A *post hoc* analysis with Bonferroni correction was performed in the case of significant ANOVA findings for multiple comparisons between variables. Effect sizes (d) were calculated according to Cohen's method, in which the magnitude of the effect was classified as small (0.20–0.49), moderate (0.50–0.79) or large (0.8) (Cohen, 1988). The α level was set at .05 for all tests. Additionally, we compared age, weight and height between groups, to explore whether the groups were homogeneous at baseline with a 1-factor ANOVA.

RESULTS

A total of 30 patients with NSCNP were included and were randomly allocated into three groups of 10 participants per group. There were no adverse events reported in either group. No statistically significant differences in demographic data were present preintervention between the groups and the self-report variables (Table 1).

Flexion range of motion

X-plane

Regarding the flexion range of motion (ROM) in the X-plane, the ANOVA revealed significant changes in group*time ($F = 4.06$, $p = .006$, $\eta_p^2 = 0.231$) and time ($F = 17.45$, $p < .001$, $\eta_p^2 = 0.393$). The *post hoc* analysis revealed significant within-group differences in both the MI and AO groups, with a moderate-large effect size for the MI group at postintervention ($p < .001$, $d = 0.95$) and at post 2 intervention ($p = .021$, $d = 0.72$), as well as with a moderate-large effect size for AO at postintervention ($p < .001$, $d = 0.96$) and at post 2 intervention ($p = .001$, $d = 0.74$). The *post hoc* analysis revealed no significant within-group differences in the PO group ($p > .05$) (Table 2). However, no significant differences were found between the groups ($p > .05$).

Y-plane

Regarding the flexion ROM in the Y-plane, the ANOVA revealed significant changes in group*time ($F = 4.14$, $p = .005$, $\eta_p^2 = 0.235$) and time ($F = 8.83$, $p < .001$, $\eta_p^2 = 0.246$). The *post hoc* analysis revealed significant within-group differences only in the AO group, with a moderate-large effect size at postintervention ($p < .001$, $d = 1.01$) and at post 2 intervention ($p = .005$, $d = 0.77$). The *post hoc* analysis revealed no significant within-group differences in the PO or MI groups ($p > .05$) (Table 2). Regarding the between groups comparison, only the AO group showed significant differences with the PO group at post 2 intervention, with a moderate effect size ($p = .035$, $d = 0.72$) (Fig. 3).

Table 1 Descriptive statistics of sociodemographic, self-reported and psychosocial data.

Measures	AO ($n = 10$)	MI ($n = 10$)	PO ($n = 10$)	p value
Age	33.5 ± 14.25	30.6 ± 11.53	27.70 ± 6.39	.520
Height (cm)	171.9 ± .80	123.10 ± .70	174 ± .40	.798
Weight (Kg)	66.7 ± 7.97	68.70 ± 4.8	69.5 ± 8.26	.672
VAS	68.9 ± 13.95	75 ± 7.73	70.8 ± 9.36	.437
Pain duration (m)	27.9 ± 17.99	26.2 ± 12.45	17.4 ± 10.05	.212
TSK-11	32.3 ± 6	33 ± 4.85	31.3 ± 3.93	.633
NDI	30.5 ± 3.62	29.8 ± 3.82	32.1 ± 4.48	.430
IPAQ	1760.6 ± 483.51	1713.85 ± 500.3	1785.7 ± 659.17	.958
MIQ-R	47.4 ± 4.77	47.3 ± 7.86	48 ± 4.52	.960
MC	3.65 ± 3.96	4.39 ± 5.7	4.71 ± 4.52	.879
Sex				.875
Male	5 (50)	5 (50)	4 (40)	
Female	5 (50)	5 (50)	6 (60)	
Educational level				.03
Secondary education	3 (30)	5 (50)	0 (00)	
College education	7 (70)	5 (50)	10 (100)	
Marital status				.136
Single	7 (70)	3 (30)	5 (50)	
Married	3 (30)	4 (40)	4 (40)	
Divorced	0 (0)	3 (30)	1 (0)	
Medication				.563
Yes	7 (70)	5 (50)	7 (70)	
No	3 (30)	5 (50)	3 (30)	
Pain Location				.530
Right	5 (50)	2 (20)	2 (20)	
Left	3 (30)	5 (50)	4 (40)	
Both	2 (20)	3 (30)	4 (40)	

Notes.
Values are presented as mean ± standard deviation or number (%).
MI, motor imagery; AO, action observation; PO, placebo observation group; TSK, Tampa Scale of Kinesiophobia; NDI, neck disability index; IPAQ, International Physical Activity Questionnaire; MIQ-R, Movement Imagery Questionnaire-Revised; MC, mental chronometry; VAS, visual analog scale.

Extension range of motion

X-plane

Regarding the extension ROM in the X-plane, there were no significant differences in time ($F = 1.87$, $p = .16$, $\eta_p^2 = 0.065$) or in group*time ($F = 0.33$, $p = .33$, $\eta_p^2 = 0.024$).

Y-lane

Regarding the extension ROM in the Y-plane, the ANOVA revealed significant changes in group*time ($F = 6.87$, $p < .001$, $\eta_p^2 = 0.337$) and time ($F = 8.56$, $p = .001$, $\eta_p^2 = 0.241$). The *post hoc* analysis revealed significant within-group differences in both the MI and AO groups, with a moderate-large effect size for MI at postintervention ($p = .017$, $d = 0.77$) and at post 2 intervention ($p = .007$, $d = 1.04$), as well as with a large effect size for AO at postintervention ($p < .001$, $d = 1.01$) and at post 2 intervention ($p = .006$, $d = 1.05$). The

Table 2 **Within-group differences in flexion cervical movement.**

Measure	Group	Mean ± SD			Mean difference (95% CI); Effect size (*d*) (a) pre–post (b) pre–post 2
		Pre	Post	Post 2	
Flexion X-plane	PO	12.0 ± 4.3	11.3 ± 4.4	12.16 ± 6.1	(a) 0.7 (−2.1 to 3.5); $d = 0.16$ (b) −0.1 (−4.0 to 3.8); $d = -0.1$
	MI	14.6 ± 6.0	9.2 ± 5.3	10.14 ± 6.4	(a) 5.4** (2.5–8.2); $d = 0.95$ (b) 4.4* (0.5–8.4); $d = 0.72$
	AO	12.6 ± 8.74	6.7 ± 7.3	6.1 ± 4.1	(a) 5.9** (3.1–8.8); $d = 0.96$ (b) 6.5* (2.6–10.4); $d = 0.74$
Measure	**Group**	**Mean ± SD**			**Mean difference (95% CI); Effect size (*d*) (a) pre–post (b) pre–post 2**
		Pre	**Post**	**Post 2**	
Flexion Y-plane	PO	9.9 ± 4.3	8.9 ± 5.4	10.8 ± 4.0	(a) 0.9 (−1.6 to 3.4); $d = 0.20$ (b) −0.9 (−3.6 to 1.8); $d = -0.21$
	MI	8.8 ± 3.6	7.6 ± 4.0	7.4 ± 4.4	(a) 1.2 (−1.3 to 3.7); $d = 0.31$ (b) 1.4 (−1.3 to 4.1); $d = 0.34$
	AO	9.4 ± 5.4	4.6 ± 3.7	5.6 ± 4.3	(a) 4.7** (2.2–7.2); $d = 1.01$ (b) 3.8* (1.0–6.5); $d = 0.72$

Notes.
* $p < .05$.
** $p < .001$.
CI, confidence interval; SD, standard deviation; PO, placebo observation group; MI, motor imagery group; AO, action observation group.

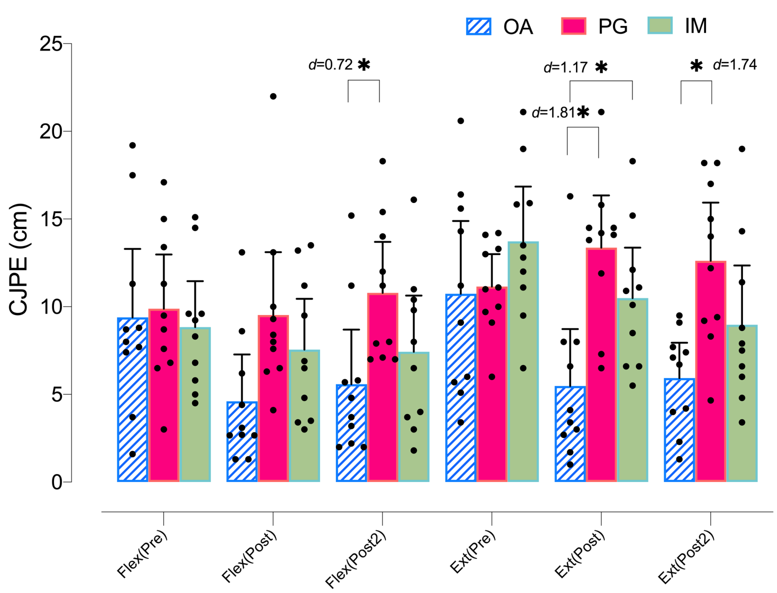

Figure 3 **Between-group differences in flexo-extension cervical movements (Y-plane).**
Full-size DOI: 10.7717/peerj.7681/fig-3

Table 3 Within-group differences in extension cervical movement.

Measure	Group	Mean ± SD			Mean difference (95% CI); Effect size (d) (a) pre–post (b) pre–post 2
		Pre	Post	Post 2	
Extension X-plane	PO	11.0 ± 3.8	10.1 ± 2.8	10.6 ± 5.6	(a) 0.9 (−2.7 to 4.6); $d = 0.27$ (b) 0.4 (−3.2 to 4.0); $d = 0.08$
	MI	9.1 ± 4.0	7.6 ± 3.3	8.8 ± 3.6	(a) 1.4 (−2.2 to 5.2); $d = 0.41$ (b) 0.3 (−3.3 to 3.9); $d = 0.07$
	AO	9.0 ± 5.5	6.9 ± 3.7	6.8 ± 3.7	(a) 2.1 (−1.5 to 5.8); $d = 0.44$ (b) 2.2 (−1.3 to 5.7); $d = 0.47$
Measure	**Group**	**Mean ± SD**			**Mean difference (95% CI); Effect size (d) (a) pre–post (b) pre–post 2**
		Pre	**Post**	**Post 2**	
Extension Y-plane	PO	11.1 ± 2.6	13.3 ± 4.1	12.6 ± 4.0	(a) −2.2 (−4.9 to 0.5); $d = -0.64$ (b) −1.4 (−5.0 to 2.1); $d = -0.44$
	MI	13.7 ± 4.3	10.5 ± 4.0	8.9 ± 4.7	(a) 3.2* (0.5–5.9); $d = 0.77$ (b) 4.7* (1.1–8.3); $d = 1.04$
	AO	10.7 ± 5.8	5.4 ± 4.5	5.9 ± 2.8	(a) 5.2** (2.5–8.0); $d = 1.01$ (b) 4.8* (1.2–8.4); $d = 1.05$

Notes.
*$p < .05$.
**$p < .001$.
CI, confidence interval; SD, standard deviation; PO, placebo observation group; MI, motor imagery group; AO, action observation group.

post hoc analysis revealed no significant within-group differences in the PO group ($p > .05$) (Table 3).

Regarding the between groups comparison, the AO group showed significant differences with both the MI and the PO groups at postintervention, with a large effect size ($p = .041$, $d = 1.17$, and $p = .001$, $d = 1.81$, respectively) and at post 2 intervention with only the PO group, with a large effect size ($p = .004$, $d = 1.74$) (Fig. 3).

Left rotation range of motion

X-plane

Regarding the left rotation ROM in the X-plane, the ANOVA revealed significant changes in group*time ($F = 3.08$, $p = .023$, $\eta_p^2 = 0.186$) but not in time ($F = 1.53$, $p = .226$, $\eta_p^2 = 0.054$). The *post hoc* analysis revealed no significant within-group differences in any group ($p > .05$) (Table 4). However, both the MI and AO groups showed significant between group differences with the PO group at postintervention, with a large effect size ($p = .035$, $d = 1.29$, and $p = .005$, $d = 1.54$, respectively) (Fig. 4).

Y-plane

Regarding the left rotation ROM in the Y-plane, the ANOVA revealed significant changes in group*time ($F = 5.44$, $p = .002$, $\eta_p^2 = 0.287$) and time ($F = 9.58$, $p = .001$, $\eta_p^2 = 0.262$). The *post hoc* analysis revealed significant within-group differences in both the MI and AO groups, with a large effect size for MI at postintervention ($p = .012$, $d = 1.18$) and at post 2 intervention ($p = .009$, $d = 0.87$), as well as with a large effect size for AO at

Table 4 Within-group differences in left rotation cervical movement.

Measure	Group	Mean ± SD			Mean difference (95% CI); Effect size (*d*) (a) pre–post (b) pre–post 2
		Pre	Post	Post 2	
Left rotation X-plane	PO	11.0 ± 4.8	12.8 ± 3.7	12.9 ± 3.6	(a) −1.8 (−4.9 to 1.2); $d = -0.42$ (b) −1.9 (−4.2 to 0.4); $d = -0.44$
	MI	9.3 ± 4.1	7.8 ± 4.1	8.4 ± 3.4	(a) 1.5 (−1.6 to 4.6); $d = 0.36$ (b) 0.9 (−1.4 to 3.3); $d = 0.24$
	AO	9.3 ± 5.3	6.3 ± 4.7	8.6 ± 4.7	(a) 2.9 (−0.1 to 6.0); $d = 0.59$ (b) 0.7 (−1.6 to 3.1); $d = 0.14$
Measure	**Group**	**Mean ± SD**			**Mean difference (95% CI); Effect size (*d*) (a) pre–post (b) pre–post 2**
		Pre	**Post**	**Post 2**	
Left rotation Y-plane	PO	10.5 ± 3.6	12.6 ± 5.3	9.7 ± 2.3	(a) −2.1 (−6.3 to 2.0); $d = -0.46$ (b) 0.7 (−2.1 to 3.6); $d = 0.26$
	MI	12.3 ± 5.1	7.1 ± 3.2	8.6 ± 2.8	(a) 5.1* (1.0–9.3); $d = 1.18$ (b) 3.6* (0.7–6.5); $d = 0.84$
	AO	11.0 ± 4.4	5.1 ± 3.3	6.4 ± 3.6	(a) 5.8* (1.6–10.0); $d = 1.71$ (b) 4.5* (1.7–7.4); $d = 1.25$

Notes.

*$p < .05$.

**$p < .001$.

CI, confidence interval; SD, standard deviation; PO, placebo observation group; MI, motor imagery group; AO, action observation group.

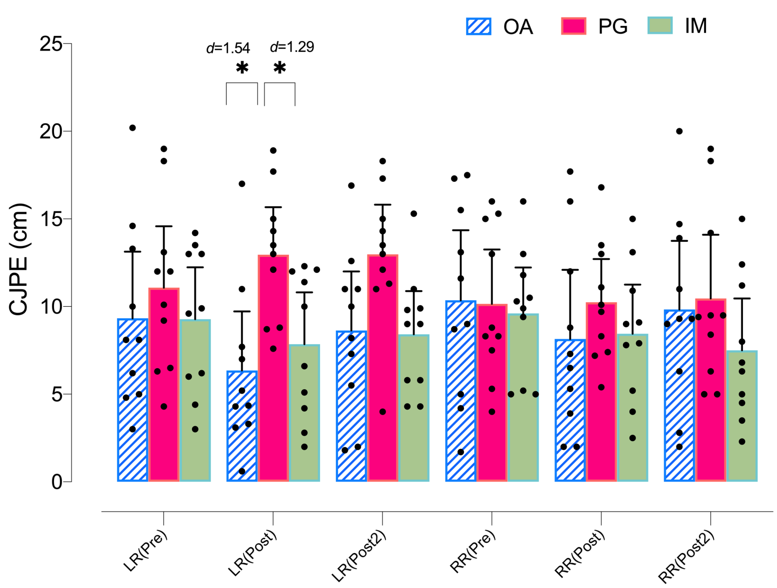

Figure 4 Between-group differences in rotation cervical movements (*X*-plane).

Full-size DOI: 10.7717/peerj.7681/fig-4

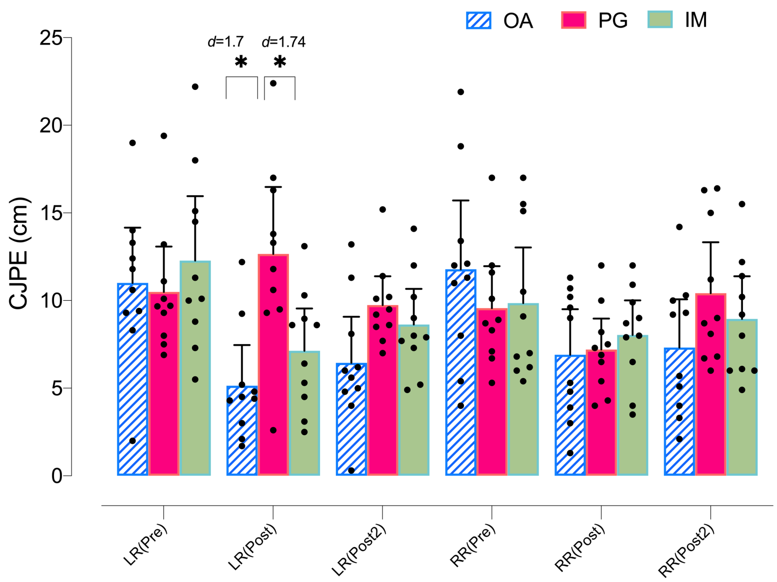

Figure 5 **Between-group differences in rotation cervical movements (*Y*-plane).**
Full-size DOI: 10.7717/peerj.7681/fig-5

postintervention ($p = .004$, $d = 1.71$) and at post 2 intervention ($p = .001$, $d = 1.25$). The *post hoc* analysis revealed no significant within-group differences in the PO group ($p > .05$) (Table 4). In addition, both the MI and AO groups showed significant between group differences with the PO group at postintervention, with a large effect size ($p = .016$, $d = 1.24$, and $p = .001$, $d = 1.70$, respectively) (Fig. 5).

Right rotation range of motion

X-plane

Regarding the right rotation ROM in the *X*-plane, the ANOVA revealed significant changes in group*time ($F = 2.81$, $p = .034$, $\eta_p^2 = 0.172$) but not in time ($F = 1.98$, $p = .147$, $\eta_p^2 = 0.069$). The *post hoc* analysis revealed significant within-group differences in the AO group, with a moderate effect size, only at postintervention ($p = .011$, $d = 0.72$). However, significant within-group differences were also found between post-post2 intervention in the AO group, showing a loss of effect after 10 min ($p = .02$, $d = -0.61$) (Table 5). Finally, no significant differences were found between the groups ($p > .05$) (Fig. 4).

Y-plane

Regarding the right rotation ROM in the *Y*-plane, the ANOVA revealed significant changes over time ($F = 7.53$, $p = .003$, $\eta_p^2 = 0.218$) but not in group*time ($F = 1.75$, $p = .151$, $\eta_p^2 = 0.115$). The *post hoc* analysis revealed significant within-group differences only in the AO group, with a large effect size, at postintervention ($p = .006$, $d = 1.24$) and at post 2 intervention ($p = .043$, $d = 0.94$). The *post hoc* analysis revealed no significant within-group differences in the PO or MI groups ($p > .05$) (Table 5). Finally, no significant differences were found between the groups ($p > .05$) (Fig. 5).

Table 5 Within-group differences in right rotation cervical movement.

Measure	Group	Mean ± SD Pre	Post	Post 2	Mean difference (95% CI); Effect size (d) (a) pre–post (b) pre–post 2
Right rotation X-plane	PO	10.1 ± 4.3	11.0 ± 4.1	10.4 ± 5.1	(a) −0.9 (−3.8 to 2.0); $d = -0.21$ (b) −0.3 (−3.6 to 3.0); $d = -0.06$
	MI	9.6 ± 3.6	8.3 ± 3.8	7.5 ± 4.1	(a) 1.2 (−1.6 to 4.2); $d = 0.35$ (b) 2.1 (−1.2 to 5.4); $d = 0.54$
	AO	10.3 ± 5.6	6.7 ± 4.5	9.8 ± 5.4	(a) 3.6* (0.7–6.5); $d = 0.72$ (b) 0.5 (−2.7 to 3.8); $d = 0.09$
Measure	**Group**	**Mean ± SD Pre**	**Post**	**Post 2**	**Mean difference (95% CI); Effect size (d) (a) pre–post (b) pre–post 2**
Right rotation Y-plane	PO	9.5 ± 3.3	7.5 ± 2.7	10.4 ± 4.0	(a) 2.0 (−2.3 to 6.4); $d = 0.66$ (b) −0.8 (−5.2 to 3.5); $d = -0.24$
	MI	9.8 ± 4.4	7.4 ± 2.6	8.9 ± 3.4	(a) 2.4 (−1.9 to 6.7); $d = 0.66$ (b) 0.9 (−3.4 to 5.2); $d = 0.22$
	AO	11.7 ± 5.4	5.9 ± 3.7	7.3 ± 3.8	(a) 5.8* (1.5–10.2); $d = 1.24$ (b) 4.4* (0.1–8.8); $d = 0.94$

Notes.
*$p < .05$.
CI, confidence interval; SD, standard deviation; PO, placebo observation group; MI, motor imagery group; AO, action observation group.

Sample size calculation

The sample size was estimated with the program G*Power 3.1.7 for Windows (G*Power from University of Dusseldorf, Germany) (*Faul et al., 2007*). The sample size calculation was considered as a power calculation to detect between-group differences in a primary outcome measures (flexion movement). We considered three groups and two measurements for primary outcomes to obtain 95% statistical power (1- β error probability) with an α error level probability of 0.05 using analysis of variance (ANOVA) of repeated measures, within-between interaction, and an effect size of $\eta p2 = 0.231$ obtained from our results. This generated a sample size of total of 42 participants plus an estimated 15% loss in follow-up, yielding a total of 48 participants (16 per group).

DISCUSSION

The main objective of the present study was to assess whether AO training and mental MI produced changes in CJPS both at the end of the intervention and at 10 min postintervention compared with a placebo intervention in patients with NSCNP.

The results obtained in the vertical plane showed that the AO group obtained greater improvements than the PO group in CJPS of the cervical extension movement both at the end of the intervention and at 10 min postintervention, as well as in the cervical flexion movement, although only at 10 min after the intervention. In addition, the AO group obtained greater improvements than the MI group in CJPS only at the end of the intervention of the cervical extension movement. However, in the horizontal plane of the flexo-extension movements, neither of the two mental practice groups was superior to the placebo intervention.

On the other hand, the results obtained in the vertical plane showed that both the AO and MI groups obtained greater improvements than the PO group in CJPS of the cervical left rotation movement at the end of the intervention. However, no significant differences were found between the groups in the right cervical rotation movement. Finally, in the horizontal plane, again both the AO and MI groups obtained greater improvements than the PO group in CJPS of the cervical left rotation movement at the end of the intervention, but no significant differences were found in the right cervical rotation movement between the groups.

NSCNP usually presents an alteration in CJPS (*Alahmari et al., 2017*). Chronic pain could affect receptors and the transmission of proprioceptive information from the cervical region, one of the keys to an adequate sense of joint position (*Uremović et al., 2007*). In addition, impaired transmission of proprioceptive information in patients with chronic musculoskeletal pain could lead to neuroplastic reorganization of body schema in the primary somatosensory area (*Kim, Kim & Nabekura, 2017*). Body schema is the model that is used by the musculoskeletal system for control, and its disruption is thought to cause incongruence between motor output and proprioceptive feedback (*Mccormick et al., 2007*). Therefore, in the current treatment of patients with NSCNP, proprioceptive training has been proposed, with the aim of improving internal representation both through exercise and manual therapy, which could reduce pain and disability in these patients (*Treleaven, 2008*). It is possible that the overlap of neural processes between MI and AO with real movement execution could provoke similar effects to real proprioceptive stimulation (*Hardwick et al., 2018*). Our results are consistent with those obtained by *Beinert et al. (2015)* in which improvements were also found in CJPS after imagination or observation of CJPS task. It is important to note that the exercises selected in the present study were specific to cranio-cervical flexo-extension movement pattern, whereas in the study mentioned above the mental practice was specific to the outcome variable. There are important differences between both types of exercise, since the mental practice of the exercises used in this study could lead to the learning of a motor gesture used in the rehabilitation of patients with NSCNP, which could lead to a difference from a clinical point of view.

It should be noted that the two movements observed or imagined by the patients in the present study were very subtle, low-joint path, highly complex, and precise movements in cervical flexo-extension, and they were the two movements exclusively performed along only the vertical plane. The findings showed that the strongest improvements obtained in CJPS were in the OA group in the same plane and in the same flex-extension movements. However, in the horizontal plane, no differences were found between the groups. These low joint range motor gestures were used because it has been found that observing full cervical movements can cause a fear response associated with movements perceived as dangerous (*La Touche et al., 2018*).

To respond to this finding, the role of mirror neurons and their relationship with the recognition of actions should be analyzed. *Rizzolatti, Fogassi & Gallese (2001)* have established the "direct-matching hypothesis". According to this hypothesis, the OA provokes an automatic activation in the observer of the same cerebral areas related to the planning and real execution of the observed action. Given the result of the activation of these neural substrates during the execution of the action is known, the observation allows the observer to understand what is being observed through a specific observation-execution matching mechanism. Perhaps due to the high complexity of craniocervical motor control gestures, along with the fact that only single-plane movements were observed and imagined, we hypothesize that the activation of neural substrates is related to the planning and execution of voluntary movements specific to that plane. This hypothesis would explain the improvements in the CJPS in the movements of the same plane but not in the horizontal plane. However, this hypothesis is only neurophysiological, because the patients' brain activity could not be observed directly. In addition, the AO and MI groups obtained greater improvements than the PO group in CJPS in terms of cervical left rotation movement; however, this result was not maintained 10 min after the intervention (post 2). There might also be a nonspecific movement plane mechanism to explain this result. Previous research has shown that mental practice provides an internal position body reference, which improves the spatiotemporal control of the position of the body in space during a dynamic movement, a critical aspect in CJPS. It has been hypothesized that both MI and AO produce better integration of motor actions due to a better internal body reference despite the absence of real movement (*Papadelis et al., 2007*). It is possible that this better internal reference of the position of the head with respect to the body could explain the positive results obtained in the left rotation, despite the fact that the mental gestures performed were in another plane of movement. However, further research is needed on the specific and nonspecific mechanisms in motor outputs induced by AO and MI.

The motor control exercises selected could influence the differences found between AO and MI training. Motor control exercises are difficult to imagine due to the fact that they require motor learning of difficult and precise movements. Previous research has shown that movement complexity and familiarity are related to MI performance (*Paris-Alemany et al., 2019*). Therefore, this intervention group might have been influenced by the difficulty of the mental motor image creation of these exercises. In addition, MI is less effective in people with less ability to perform it (*Patterson et al., 2006*), and it is well known that patients with chronic pain have a decreased ability to create mental motor images, which could also have affected our results (*Breckenridge et al., 2019*). Thus, taking into account all these variables, significant mental effort is required, which the patients might not have been able to achieve (*Cuenca-Martínez et al., 2018*; *Decety et al., 1991*). Regarding mental practice intervention duration, a meta-analysis by *Driskell, Copper & Moran (1994)* proposed a MI intervention for approximately 20 min is ideal to obtain the maximum benefit from MI. Therefore, *Hinshaw (1991)* suggest that MI duration from 10 to 15 min was required for the optimal effect on performance. Perhaps the short intervention time was insufficient to solve these challenges. In addition, *Gonzalez-Rosa et al. (2015)* have shown that AO provokes greater activation of cortical areas during motor learning and induces better motor learning results in comparison with MI. *Taube et al. (2015)* showed that cortical activity was higher during the combination of AO and MI, so it is possible that best training effects should be expected when participants apply MI during AO.

Moreover, previous studies have shown that AO could activate in a more ecological way the mirror neuron system in front of the MI (*Gatti et al., 2013*). The reason for this difference is that the ventral premotor cortex receives visual inputs and could be more activated by actual visual input than by the absence of visual input or overt movement, as in the case of motor imagery (*Rizzolatti & Luppino, 2001*). In addition, during AO, the observer has a model who performs the action and in the correct context. In contrast, during motor imagery, the individual must rehearse the relevant motor representations and covertly perform the action, and this could be especially relevant in subjects with diminished imagery ability, as mentioned above (*Gatti et al., 2013*; *Mulder, 2007*). This could lead to better motor learning via AO of new and highly complex tasks (*Mulder et al., 2004*), such as those included in the exercises in this study.

Finally, it is important to note that other therapeutic options have been used to improve cervical motor control in patients with NSCNP. For example, *Martín-Rodríguez et al. (2019)* recently found that dry needling both inside and outside the myofascial trigger point in the sternocleidomastoid muscle led to improvements in cervical motor control. In addition, *Sterling, Jull & Wright (2001b)* found that spinal manual therapy provoked a decreased activity of the superficial flexor muscle of the neck in a cervical motor control test. Therefore, in future studies, it would be interesting to compare the effect of mental practice against or even in combination with these therapeutic options.

Clinical implications

The high prevalence of patients with chronic pain, and especially with NSCNP, makes it one of the most relevant musculoskeletal disorders in the rehabilitation sciences (*Vos et al., 2013*). It is therefore essential to develop new approaches to rehabilitation strategies. In this regard, motor control exercises have been shown to decrease pain and disability in patients with NSCNP compared with other types of treatment (*Martin-Gomez et al., 2019*). However, the clinical implementation of this type of exercise in a clinical context is challenging, due to its high complexity or the pain itself leading patients to not perform it or to perform it incorrectly, reducing its therapeutic potential. In this regard, both MI and AO provide a simple, clinically therapeutic alternative at low cost that can be performed independently by the patient. The results of this study suggest that mental practice can be a useful therapeutic strategy in patients with NSCNP, especially in the early stages of rehabilitation, and both strategies should be considered for patients with NSCNP.

Limitations

This study presents several limitations. First, the sample size is small; thus, the results should be considered with caution. In addition, the results have only been considered in the short term, and the duration and type of intervention might be insufficient for greater increases in CJPS in patients with NSCNP. *Hinshaw (1991)* have found that the optimal time for MI to provide the greatest benefits is between 10 and 15 min. In the present study, the duration of the MI intervention was 4 min. This length of time might not be sufficient to obtain the full potential of MI. Further research is needed to determine the role of mental practice in the rehabilitation process of patients with NSCNP.

CONCLUSIONS

The results obtained in the present study showed that the AO group obtained greater improvements than the PO group in CJPS for the cervical extension movement both at the end of the intervention and 10 min postintervention, as well as in the cervical flexion movement, although only at 10 min postintervention. In addition, the AO group obtained greater improvements than the MI group in the CJPS only at the end of the intervention in the cervical extension movement. Finally, regarding the left rotation cervical movement, both MI and AO were superior to PO in both planes at the end of the intervention.

Our results suggest that AO training is an effective sensorimotor neurotraining tool to improve CJPS in the early stages of treatment. In addition, MI could also be a tool to consider using in rehabilitation, but perhaps with a longer training time. The therapeutic potential of the application of mental practice in a clinical context in the early stages of rehabilitation of NSCNP should be considered.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

The authors received no funding for this work.

Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Ferran Cuenca-Martínez conceived and designed the experiments, performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft.
- Roy La Touche conceived and designed the experiments, analyzed the data, contributed reagents/materials/analysis tools, authored or reviewed drafts of the paper, approved the final draft.
- Jose Vicente León-Hernández analyzed the data, authored or reviewed drafts of the paper, approved the final draft.
- Luis Suso-Martí conceived and designed the experiments, performed the experiments, analyzed the data, authored or reviewed drafts of the paper, approved the final draft.

Clinical Trial Ethics

The following information was supplied relating to ethical approvals (i.e., approving body and any reference numbers):

La Salle University Center for Higher Education granted Ethical approval to carry out the present study (Ethical Application Ref: 027/2019).

Data Availability

The following information was supplied regarding data availability:

The raw measurements are available in Supplemental File.

Clinical Trial Registration

The following information was supplied regarding Clinical Trial registration:

The trial registry number is NCT03910829.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.7681#supplemental-information.

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Effects of movement representation techniques on motor learning of thumb-opposition tasks

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The present work is the first study that assess long run change after motor learning. The study's main objective was to evaluate the short to medium-term impact of motor imagery (MI) and action observation (AO) on motor learning of a sequence of thumb-opposition tasks of increasing complexity. We randomly assigned 45 participants to an AO, MI, or placebo observation (PO) group. A sequence of 12 thumb-opposition tasks was taught for 3 consecutive days (4 per day). The primary outcome was accuracy. The secondary outcomes were required time and perfect positioning. The outcomes were assessed immediately after the intervention and at 1 week, 1 month and 4 months postintervention. Regarding the primary outcome, AO group had significantly higher accuracy than the MI or PO group until at least 4 months ($p<0.01$, $d>0.80$). However, in the bimanual positions, AO was not superior to MI at 1 week postintervention. Regarding secondary outcomes, AO group required less time than the MI group to remember and perform the left-hand and both-hand gestures, with a large effect size ($p<0.01$, $d>0.80$). In terms of percentage of perfect positions, AO group achieved significantly better results than the MI group until at least 4 months after the intervention in the unimanual gestures ($p<0.01$, $d>0.80$) and up to 1 month postintervention in the bimanual gestures ($p=0.012$, $d=1.29$). AO training resulted in greater and longer term motor learning than MI and placebo intervention. If the goal is to learn some motor skills for whatever reason (e.g., following surgery or immobilization.), AO training should be considered clinically.

The motor learning of complex tasks involves a series of closely linked neurophysiological processes, which include motor output, somatosensory afferences, and central processing to establish certain movement parameters (e.g., strength, speed, and direction)[1].

Mental practice applied to motor learning has been widely studied in the field of cognitive neurosciences and sports psychology. The "functional equivalence" hypothesis[1] proposes that mental simulation processes share certain cerebral representations along with processes of preparation and real motor execution[3]. Neuroimaging studies have revealed that, during mental practice, there is neurophysiological activation of the brain areas involved in the planning and execution of voluntary movement (primary motor cortex, supplementary motor area, cerebellum, premotor area, the inferior and superior parietal lobule and the basal ganglia) similar to the processes when the movement is actually performed[4,5].

Two well-known methods for motor skill learning are action observation (AO) and motor imagery (MI), the latter of which is defined as a dynamic mental process that involves the internal representation of an action without its actual motor output[6]. MI has been shown to facilitate the motor learning of various skills in certain contexts and settings such as golf[7] tennis[8] trampoline routines[9], music[10] dance[11] and even surgical skills[12].

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AO, however, evokes an internal, real-time simulation of the actions being observed[13] AO provokes an automatic activation in the observer of the same cerebral areas related to the planning and actual execution of the observed action[14]. Previous studies have shown that AO can lead to the motor learning of gestures observed from the visual information acquired, even without their actual execution[15].

Growing scientific interest in the role of mental practice in motor learning has led to further studies to clarify the differences between AO and MI in improving motor performance. Although both processes appear to be effective, previous studies have shown that AO appears to be more effective than MI, at least in the rapid early phase of motor learning[16,17]. However, there is still a lack of scientific literature regarding the potential of these techniques and whether they can, in isolation, consolidate the learning of new motor gestures in the short/medium term with a minimal training. The potential for minimal intervention over time has not yet been investigated. This may offer interesting data when it comes to guiding the dosage of mental practice, an aspect with a lack of consensus so far. It is important to stress that MI has a relevant distinctive feature. Subjects can create changing scenes and diverse situations through MI. It is therefore that the main advantage of MI compared with AO is that scenarios can be changed and adapted to the subject's context.

One of the most studied body regions in the field of mental practice are the hands, due to their high functionality and significance[18–20]. To our knowledge, however, there have been no research studies that have evaluated motor learning through thumb-opposition specific tasks. The thumb is frequently used in daily life activities and leading to a learning process in this body region could have a significant impact on people's lives. Clinically, improved neuro-sensorimotor control, leading to a process of motor relearning after prolonged disuse and improving certain peripheral physical variables, such as strength and active range of motion, could be key aspects for reducing disability and increasing functionality[21, 22]. Another key aspect that we think will be able to influence the motor learning process through movement representation techniques is the ability to imagine movements. It has been argued that the ability to imagine is an important factor when performing mental practice[22]. For example, Martin et al.[23] have suggested that an individual's ability to imagine movements can determine the effectiveness of its use. The authors hypothesize that good imager is expected to show greater benefits resulting from practice.

Therefore, the primary objective of the present study was to evaluate the short to medium-term impact of MI and AO in isolation on the motor learning of a sequence of manual motor positions of increasing complexity in terms of accuracy compared with a placebo intervention. The secondary objectives were to evaluate the required time and the percentage of perfect positions that resulted from these mental practice interventions compared with a placebo intervention (also in the short to medium term). In addition, we also aimed to assess the effects on motor learning based on the ability to imagine movements in order to verify whether good imagers showed greater benefits than poor imagers accordingly to each intervention.

Methods

Study design. We conducted a single-blind randomized controlled study whose protocol followed the Consolidated Standards of Reporting Trials (CONSORT) statement on randomized trials of nonpharmacological treatments[23].

Participant recruitment. A total of 45 asymptomatic volunteers were recruited between October 2018 and June 2019 from the local community through social media and e-mail. The inclusion criteria were as follows: (a) no symptoms and (b) age 18–65 years. The exclusion criteria were the following: (a) any knowledge of physical therapy or movement representation techniques; (b) age younger than 18 years; (c) pain at the time of the study; and (d) any type of neurological disease. All data were collected at the La Salle University Center for Advanced Studies.

Randomization. Randomization was performed using a computer-generated random sequence table with a balanced 3-block design (GraphPad Software, Inc., CA, USA). An independent researcher generated the randomization list, and a research team member who was not involved in the assessment or intervention of the participants was in charge of the randomization and maintained the list. Those included were randomly assigned to one of the three groups using the random sequence list, ensuring concealed allocation.

Blinding. The assessments and interventions were performed by different researchers. The evaluator was blinded to the participant's assignment when performed the measurements and recorded the data. The participants were asked not to make any comments to the researcher performing the measurements. It is therefore that the evaluator did not know at any time what intervention each participant had received at the time of the results assessment.

Interventions. *Motor imagery.* All participants in the MI group were informed of the procedure at the beginning of the intervention and underwent a familiarization session regarding the intervention they were going to perform. The participants were asked to memorize the following numbering system for the fingers of each hand:

- For the left hand: number 2 for the second finger (index finger), number 3 for the third finger, number 4 for the fourth finger and number 5 for the fifth finger.
- For the right hand: number 6 for the fifth finger, number 7 for the fourth finger, number 8 for the third finger and number 9 for the second finger (Supplementary Appendix 1).

This method of attributing numbers to fingers to perform motor imagination tasks is similar to that done by Debarnot et al.[24] This familiarization and memorization session was separate from the training sessions and did not include any positions that were to be evaluated later.

After the participants had memorized this step, they underwent kinesthetic MI training (from a first-person perspective) for each of the 12 manual positions (Supplementary Appendices 2, 3) included in the present study on 3 consecutive training days (see "Procedures" section). In the kinesthetic MI tasks, the participants were asked to imagining feeling the movements, positions, sensations, etc., without actually performing the hand motor gestures.

The researcher announced a sequence of numbers (2–5 for the left hand, 6–9 for the right hand), which the participants were asked to imagining feeling the movements in the first person using each of the 12 manual motor gestures. To prevent the participants from performing arithmetic tasks to memorize the numbers instead of imagining feeling the movements, an ordinal nomenclature was employed (e.g., second, fourth, sixth, etc.), and the participants were guided during each series of mental tasks so that they performed each opposition task during the 30 s of each series.

Action observation. The AO group performed the same motor sequences described for the MI group but by watching videos of each motor gesture, which had the same duration and frequency of movement as for the MI group in the first-person perspective. The sequence of gestures is detailed in the Procedures section. It is therefore that both MI and AO groups performed the same procedure but the first one imagined feeling the movements and the second one observed the movements.

Placebo observation group. In the placebo observation (PO) group, participants watched videos representing scenes from a documentary without human agents, a "sham" intervention similar to that conducted by Bassolino et al.[25].

Procedures. After giving their consent to partake in the study and prior to the intervention, all participants were given a set of questionnaires. These included a sociodemographic assessment and an evaluation of their physical activity, hand laterality recognition, mental chronometry (MC) and ability to imagine movements. The assessments were designed to have all participants start with the same mental state. The questionnaires were the Spanish-validated version of the International Questionnaire of Physical Activity (IPAQ) and the Spanish-validated version of the Revised Movement Imagery Questionnaire (MIQ-R).

After the baseline assessment was completed, each participant underwent a total of 4 consecutive days of training and assessment. On the first day, the training for the 4 left-hand positions (unimanual positions) was performed (Supplementary Appendix 2). A total of 30 s was spent performing each of the positions (2 min in total), which were performed twice, for a total intervention duration of 4 min. On the second day, the four positions of the right hand were taught in the same manner as the left hand, also with a total intervention duration of 4 min (Supplementary Appendix 2). On the third day, the four positions that included both hands simultaneously (bimanual positions) were taught, spending the same amount of time as the previous days (4 min in total) (Supplementary Appendix 3). On the fourth day, only one evaluation of the 12 sequences of manual motor positions was performed (postintervention evaluation). The duration of the evaluation was approximately 20–25 min. Subsequently, an evaluation was conducted 1 week after the intervention (1-week post), 1 month after the intervention (1-month post) and finally 4 months after the intervention (4-month post). The duration of each follow-up assessment was similar, with 20–25 min spent. During the assessment, the participant never knew the score obtained. No feedback was ever given.

Outcome measures. *Primary outcome.* Accuracy. The accuracy was calculated as follows: each motor gesture in the thumb-opposition tasks involved four fingers in the unimanual gestures and eight fingers in the bimanual gestures (excluding the thumb/s). In the assessment, each subject was asked to place each gesture (one by one) in a real way. In each placement, the time needed by each subject to place the hands gesture was recorded and the hits/success were counted. "Accuracy" refers to the percentage of hits on each of the manual gestures when these were assessed. In unimanual positions, as there are four fingers, each finger that was correct in the position adds up to 25%. Thus, if all four fingers are correctly placed, the "accuracy" is 100%. If there are three fingers placed correctly and one wrong, then the "accuracy" is 75%. If two fingers are positioned correctly and two are positioned incorrectly, then the "accuracy" is 50%, etc. Each success accounted for 12.5% (instead of 25%) of the total score in the bimanual gestures. A participant was considered to have made an error when the two opposing fingers did not perform the gesture or performed a gesture when not appropriate. For example, if a participant performed three correct and five incorrect gestures during a bimanual task (either by not placing the fingers when required or placing the fingers when not required), they would score 3/8 (accuracy = 37.5%) for the task.

Secondary outcomes. Required time. The time required to position each manual motor gesture from the evaluator's indication to the participant's action was recorded in seconds using a stopwatch.

Perfect positions. The aim of this variable was to assess the number of positions performed perfectly (i.e., no errors, with a maximum score of 4/4 [100%] for the unimanual and bimanual gestures). Both hands had to perform the position without any error for it to count as perfect. The percentage of perfect positions could range from 0–100%. For example, if a participant obtained a score of 75% in task 1, 100% in task 2, 50% in task 3 and 100% task 4, then only 2 of the 4 positions were perfect, resulting in a score of 2/4 (50%).

Baseline outcomes. Visual and kinesthetic motor imagery ability. To assess motor imagery ability, we employed the MIQ-R which consists of four movements repeated in two domains (visual and kinesthetic). Depending on the perceived difficulty, participants score the movements from 1 to 7, with one representing the maximum difficulty in creating mental motor imagery and seven representing the least difficulty. The psychometric properties of MIQ-R have been consistently adequate, with Cronbach's α coefficients ranging above 0.84 for the entire scale, 0.80 for the visual domain and 0.84 for the kinesthetic domain[26].

Mental chronometry. MC is a reliable and widely used tool for recording objective measurements of the ability to create mental motor images[27,28]. For the MC assessment, we used a stopwatch to record the time spent by each participant on imagining the mental tasks included in the MIQ-R. The evaluator issued a command to start imagining the task, and the participant performed a verbal sign once the task had been completed. The time between the two interval commands was recorded, as was the time dedicated by each participant to the real-time execution of the task. The MC values are expressed as the time congruence between the two tasks. The inter-rater intraclass correlation coefficient (ICC) for MC ranged from 0.63–0.95, whereas the ICC for intrasession reliability ranged from 0.95–0.97[27].

Physical activity level. We employed IPAQ to assess the participants' physical activity level and assign to one of three activity groups (high, moderate and low/sedentary)[29]. The questionnaire's psychometric properties have been accepted for use in studies that measure physical activity; IPAQ has a reliability of approximately 0.65 ($r = 0.76$; 95% CI 0.73–0.77)[30].

Laterality recognition task. For the hand laterality recognition task, we evaluated two aspects: (1) the percentage of correct answers for laterality discrimination, which is the ability to recognize whether a body part belongs to the right or left side of the body[31] and (2) the response time employed by the participants for the discrimination task or cognitive judgment. We employed the Recognise Online application designed and developed by the NOI group (Neuro Orthopaedic Institute)[32] whose reliability has been previously established in populations with and without chronic pain[32]. The ICC response time was described for only the feet (ICC 0.63–0.75) and trunk (ICC 0.51–0.91).

Data analysis. We employed the Statistical Package for the Social Sciences (SPSS 23.00, IBM, Chicago, IL, USA) for the data analysis, employing a confidence interval of 95% and considering all variables with a p value < 0.05 as statistically significant. We used descriptive statistics to summarize the data for continuous variables, which are presented as mean ± standard deviation with 95% confidence intervals. The categorical variables are presented as absolute numbers or relative frequencies (percentages). To compare the categorical variables, we employed a chi-squared test with residual analysis. The normal distribution of all primary and secondary measures was assessed using the Shapiro–Wilk test. We performed a repeated measures analysis of variance (ANOVA) to study the effect of the interparticipant factor "intervention group" (consisting of three categories: AO, MI and PO) and the intraparticipant factor "time" (consisting of four categories: postintervention, 1 week postintervention, 1 month postintervention and 4 months postintervention) on the dependent variables. We calculated the partial eta squared (η_p^2) as a measure of the effect size (strength of association) for each main effect and interaction in the ANOVAs, with 0.01–0.059 representing a small effect, 0.06–0.139 a medium effect and > 0.14 a large effect. We performed a post hoc analysis with Bonferroni correction in the case of significant ANOVA findings for multiple comparisons between variables. We calculated the effect size (Cohen's d) for the main variables, considering 0.20–0.49, 0.50–0.79 and > 0.80 to be small, medium and large effect sizes, respectively[33]. In addition, a secondary analysis was conducted to determine if the ability to imagine movements could have an impact on the results obtained, especially for the MI group. For this purpose, we calculated the median score for MI group of the participants in the MIQ-R questionnaire and classified the participants into "good imagers" (those above median) or "poor imagers" (those below median). The same analysis that was done for the MI group was also done with the other two groups (AO and PO).

Ethical approval. All procedures were approved by the Human Research Ethics Committee of the La Salle University Center for Advanced Studies (CSEULS-PI-013/2019). The study was registered in the United States Randomized Trials Register on clinicaltrial.gov (trial registry number: NCT03769974).

Informed consent and ethics. All participants granted their informed written consent prior to inclusion and were provided an explanation of the study procedures, which were planned under the ethical standards of the Helsinki Declaration.

Results

A total of 45 asymptomatic participants were included and randomly allocated to 3 groups of 15 participants each. No adverse events or loss to follow-up were reported for any group. There were no statistically significant differences in demographic data prior to the intervention between the groups and the self-reported variables, except for body mass index ($p = 0.02$) (Table 1).

Measures	MI (n = 15)	AO (n = 15)	PO (n = 15)	*p*-value
Age (year)	32.0 ± 12.5	32.9 ± 14.0	29.3 ± 6.7	0.66
BMI (kg/m^2)	23.4 ± 2.2	20.8 ± 1.9	23.7 ± 2.4	0.02*
MIQ-R	48.3 ± 6.6	50.4 ± 5.1	48.6 ± 6.5	0.59
MIQ-RK	23.6 ± 3.6	24.2 ± 4.6	24.4 ± 3.1	0.84
MIQ-RV	24.6 ± 3.4	26.2 ± 1.7	24.2 ± 3.6	0.16
MC	1.28 ± 0.3	1.13 ± 0.2	1.42 ± 0.4	0.13
K-MC	1.36 ± 0.4	1.22 ± 0.3	1.45 ± 0.5	0.16
V-MC	1.19 ± 0.3	1.04 ± 0.3	1.41 ± 0.5	0.06
LRT %Total	80.3 ± 10.7	85.0 ± 9.1	81.6 ± 6.9	0.35
LTT %Right Hand	78.0 ± 16.5	84.6 ± 9.9	84.0 ± 9.1	0.27
LRT %Left Hand	82.7 ± 7.9	84.0 ± 9.1	79.3 ± 11.6	0.40
LRT Time	2.4 ± 0.8	2.2 ± 0.3	2.1 ± 0.3	0.35
LRT Right-Hand Time	2.2 ± 0.8	2.2 ± 0.4	2.2 ± 0.5	0.96
LRT Left-Hand Time	2.5 ± 1.1	2.2 ± 0.3	2.0 ± 0.7	0.18
IPAQ	2,879.5 ± 1,443.1	2,589.2 ± 1,238.6	2077.9 ± 1,164.8	.430
IPAQ-Level				0.14
Low	0 (0)	0 (0)	0 (0)	
Moderate	10 (66.7)	10 (66.7)	14 (93.3)	
High	5 (33.3)	5 (33.3)	1 (6.7)	
Sex				0.91
Male	9 (60)	8 (53.3)	9 (60)	
Female	6 (40)	7 (46.7)	6 (40)	
Educational level				0.88
Secondary education	3 (20)	4 (26.7)	4 (26.7)	
College education	12 (80)	11 (73.3)	11 (73.3)	
Dominant hand				0.34
Right	14 (93.3)	15 (100)	13 (86.7)	
Left	1 (6.7)	0 (0)	2 (13.3)	

Table 1. Descriptive statistics for the sociodemographic and self-reported data. Values are presented as mean ± standard deviation or number (%). *AO* action observation, *BMI* body mass index, *IPAQ* International Physical Activity Questionnaires, *K* kinesthetic subscale, *LRT* laterality recognition task, *MI* motor imagery, *MIQ-R* movement imagery questionnaire-revised, *MC* mental chronometry, *PO* placebo observation group, *V* visual subscale, %, successful.

Primary outcome. *Accuracy.* In terms of the left hand, the ANOVA revealed significant changes during group × time (F = 2.84, p = 0.023, η_p^2 = 0.119) and time (F = 21.19, p < 0.001, η_p^2 = 0.335). The post hoc analysis showed that the MI and AO groups showed statistically significant differences compared with the PO postintervention (p < 0.001; d = 2.65, and d = 4.78, respectively), 1 week postintervention (p < 0.001; d = 1.94, and d = 4.45, respectively) and 1 month postintervention (p < 0.001; d = 1.58, and d = 2.90, respectively), with a large effect size. However, only the AO group showed significant differences compared with the PO group at 4 months postintervention, with a large effect size (p < 0.001, d = 2.25). The AO was also superior to the MI group at 1 week (p = 0.034, d = 0.99), 1 month (p = 0.016, d = 0.98) and 4 months (p = 0.003, d = 1.10) postintervention, with a large effect size. However, there were no differences between the 2 mental practice groups postintervention (p > 0.05). The intragroup differences are summarized in Table 2.

In terms of the right hand, the ANOVA revealed significant changes during group × time (F = 2.39, p = 0.048, η_p^2 = 0.102) and time (F = 24.12, p < 0.001, η_p^2 = 0.365). The post hoc analysis showed that the MI and AO groups showed statistically significant differences compared with the PO group postintervention (p < 0.01; d = 1.23, and d = 2.97, respectively), 1 week postintervention (p < 0.01; d = 1.18, and d = 3.06, respectively) and 1 month postintervention (p < 0.01; d = 1.08, and d = 2.44, respectively), with a large effect size. However, only the AO group showed significant differences compared with the PO group at 4 months postintervention, with a large effect size (p < 0.001, d = 2.85). The AO group was also superior to the MI group postintervention (p = 0.04, d = 0.95), 1 week postintervention (p = 0.045, d = 0.90), 1 month postintervention (p = 0.02, d = 0.94) and 4 months postintervention (p < 0.001, d = 1.49), with a large effect size. The intragroup differences are summarized in Table 2.

In terms of both hands, the ANOVA revealed significant changes during group × time (F = 3.03, p = 0.017, η_p^2 = 0.126) and time (F = 19.19, p < 0.001, η_p^2 = 0.314). The post hoc analysis showed that the MI and AO groups showed statistically significant differences compared with the PO post postintervention (p < 0.05; d = 0.85 and d = 4.02, respectively), 1 week postintervention (p < 0.001; d = 1.59 and d = 2.28, respectively), 1 month postintervention (p < 0.001; d = 1.50 and d = 5.42, respectively) and 4 months postintervention (p < 0.001; d = 1.38 and d = 3.08, respectively), with a large effect size. The AO group was also superior to the MI group postintervention

Measure	Group	Mean ± SD				Mean difference (95% CI); effect size (*d*) (a) post—1 week (b) post—1 month (c) post—4 months
		Post	1 week	1 month	4 months	
Left hand	PO	56.6 ± 12.6	51.6 ± 14.2	52.9 ± 12.4	45.8 ± 9.9	(a) 5.0 (− 4.6 to 14.6); *d* = 0.37 (b) 3.7 (− 6.9 to 14.4); *d* = 0.29 (c) 10.8 (− 4.3 to 26.0); *d* = 0.95
	MI	93.7 ± 15.3	84.1 ± 18.8	77.9 ± 18.4	59.6 ± 22.5	(a) 9.6 (− 0.1 to 19.2); *d* = 0.56 (b) 15.8* (5.1 to 26.5); *d* = 0.93 (c) 34.1** (18.9 to 49.3); *d* = 1.77
	AO	99.5 ± 1.6	97.5 ± 3.1	95.0 ± 16.2	84.1 ± 21.8	(a) 2.1 (− 7.5 to 11.7); *d* = 0.81 (b) 4.5 (− 6.1 to 15.2); *d* = 0.39 (c) 15.4* (0.2 to 30.6); *d* = 0.99
Right hand	PO	53.7 ± 17.8	55.4 ± 15.2	53.7 ± 12.4	40.8 ± 11.7	(a) − 1.6 (− 8.3 to 4.9); *d* = − 0.1 (b) 0 (− 10.0 to 10.0); *d* = 0 (c) 12.9* (0.9 to 24.9); *d* = 0.85
	MI	78.7 ± 22.5	77.9 ± 22.0	74.1 ± 21.7	53.3 ± 23.8	(a) 0.8 (− 5.7 to 7.4); *d* = 0.03 (b) 4.5 (− 5.5 to 14.6); *d* = 0.2 (c) 25.4** (13.4 to 37.4); *d* = 1.09
	AO	95.0 ± 8.2	92.9 ± 8.1	92.0 ± 15.9	85.41 ± 18.7	(a) 2.08 (− 4.5 to 8.7); *d* = 0.25 (b) 2.97 (− 7.2 to 13.0); *d* = 0.23 (c) 9.6 (− 2.4 to 21.5); *d* = 0.66
Both hands	PO	57.9 ± 11.6	49.1 ± 21.8	43.7 ± 6.8	41.7 ± 5.0	(a) 8.7 (− 2.2 to 19.7); *d* = 0.5 (b) 14.1** (6.3 to 22.0); *d* = 1.49 (c) 16.2** (6.8 to 25.5); *d* = 1.81
	MI	72.0 ± 20.4	82.5 ± 19.9	66.2 ± 19.8	61.4 ± 19.5	(a) − 10.4 (− 21.4 to 0.6); *d* = − 0.52 (b) 5.8 (− 1.9 to 13.7); *d* = 0.28 (c) 10.6* (1.3 to 19.9); *d* = 0.53
	AO	94.7 ± 5.6	90.8 ± 13.7	89.7 ± 9.8	78.0 ± 15.8	(a) 3.9 (− 7.0 to 14.9); *d* = 0.37 (b) 5.0 (− 2.7 to 12.9); *d* = 0.62 (c) 16.8** (7.4 to 26.1); *d* = 1.40

Table 2. Intragroup differences in the accuracy (%) outcome measure. *p < 0.05; **p < 0.001. *AO* action observation group, *CI* confidence interval, *m* month, *MI* motor imagery group, *PO* placebo observation group, *SD* standard deviation, *w* week.

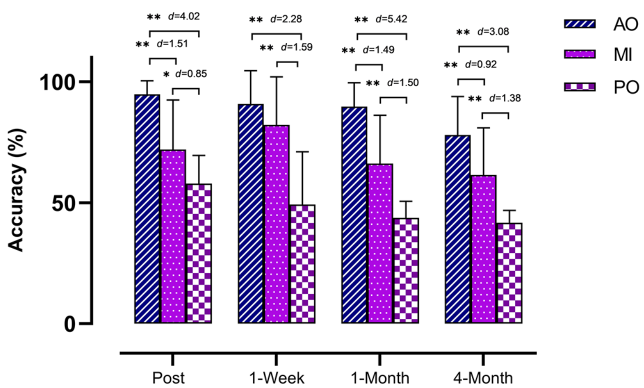

Figure 1. Between-group differences in accuracy (%) outcome measure regarding bimanual gestures. *p < 0.05; ** p < 0.001; *AO* action observation, *MI* motor imagery, *PO* placebo observation group, *d* d of Cohen.

($p < 0.001$, $d = 1.51$), 1 month postintervention ($p < 0.001$, $d = 1.49$) and 4 months postintervention ($p = 0.012$, $d = 0.92$), with a large effect size. There were no significant differences 1 week postintervention between the MI and AO groups ($p > 0.05$) (Fig. 1). The intragroup differences are summarized in Table 2.

Secondary outcomes. *Required time.* In terms of the left hand, the ANOVA revealed significant changes during group × time ($F = 4.75$, $p = 0.001$, $\eta_p^2 = 0.185$) and time ($F = 3.56$, $p = 0.029$, $\eta_p^2 = 0.078$). The post hoc analysis showed that the MI group spent significantly more time than the AO group at 1 month ($p < 0.001$, $d = 1.46$) and 4 months ($p = 0.003$; $d = 1.07$) postintervention, with a large effect size. The AO group needed more time than the PO group only at 4 months postintervention, with a large effect size ($p = 0.025$, $d = 1.47$). The MI group spent significantly more time than the PO group at 1 week ($p = 0.021$, $d = 1.04$), 1 month ($p = 0.009$, $d = 1.03$) and 4 months ($p < 0.001$, $d = 2.21$) postintervention, with a large effect size. The intragroup differences are shown in Table 3.

Measure	Group	Mean ± SD				Mean difference (95% CI); effect size (*d*) (a) post—1 week (b) post—1 month (c) post—4 months
		Post	1 week	1 month	4 months	
Left hand, s	PO	1.72 ± 0.9	1.19 ± 0.4	1.42 ± 0.3	1.07 ± 0.1	(a) 0.53* (0.0 to 1.0); *d* = 0.76 (b) 0.3 (− 0.2 to 0.8); *d* = 0.44 (c) 0.65* (0.1 to 1.2); *d* = 1.01
	MI	1.94 ± 0.7	1.72 ± 0.6	1.92 ± 0.5	2.32 ± 0.7	(a) 0.21 (− 0.3 to 0.7); *d* = 0.33 (b) 0.01 (− 0.5 to 0.5); *d* = 0.03 (c) − 0.38 (− 0.9 to 0.1); *d* = − 0.54
	AO	1.39 ± 0.5	1.35 ± 0.5	1.24 ± 0.3	1.62 ± 0.5	(a) 0.03 (− 0.5 to 0.5); *d* = 0.08 (b) 0.15 (− 0.3 to 0.6); *d* = 0.36 (c) − 0.23 (− 0.8 to 0.3); *d* = − 0.46
Both hands, s	PO	2.82 ± 1.2	2.84 ± 1.3	2.18 ± 0.8	1.38 ± 0.6	(a) − 0.02 (− 1.0 to 0.9); *d* = − 0.02 (b) 0.64 (− 0.2 to 1.5); *d* = 0.95 (c) 1.43* (0.4 to 2.4); *d* = 2.6
	MI	4.54 ± 1.8	3.48 ± 1.5	3.49 ± 1.4	3.5 ± 1.1	(a) 1.06* (0.0 to 2.0); *d* = 0.64 (b) 1.05* (0.1 to 1.9); *d* = 0.65 (c) 1.04* (0.0 to 2.0); *d* = 0.69
	AO	1.91 ± 0.7	1.75 ± 0.6	1.81 ± 0.5	2.4 ± 0.8	(a) 0.16 (− 0.8 to 1.1); *d* = 0.24 (b) 0.09 (− 0.7 to 0.9); *d* = 0.16 9c) − 0.48 (− 1.5 to 0.5); *d* = − 0.65

Table 3. Intragroup differences in requested time outcome measurement. *p < 0.05; **p < 0.001. *AO* action observation group, *CI* confidence interval, *m* month, *MI* motor imagery group, *PO* placebo observation group, *s* seconds, *SD* standard deviation, *w* week.

In terms of the right hand, the ANOVA revealed no significant differences in time ($F = 1.68$, $p = 0.18$, $\eta_p^2 = 0.038$) or in group × time ($F = 2.10$, $p = 0.071$, $\eta_p^2 = 0.091$).

In terms of both hands, the ANOVA revealed significant changes during group × time ($F = 5.02$, $p < 0.001$, $\eta_p^2 = 0.193$) and time ($F = 4.72$, $p = 0.004$, $\eta_p^2 = 0.101$). The post hoc analysis showed that the MI group spent significantly more time than the AO group postintervention ($p < 0.001$, $d = 1.90$), 1 week ($p = 0.002$, $d = 1.44$), 1 month postintervention ($p < 0.001$, $d = 1.58$) and 4 months postintervention ($p = 0.004$, $d = 1.11$), with a large effect size. The AO group needed more time than the PO group only at 4 months postintervention, with a large effect size ($p = 0.009$, $d = 1.34$). The MI group spent significantly more time than the PO group postintervention ($p = 0.003$, $d = 1.11$), 1 month postintervention ($p = 0.002$, $d = 1.13$) and 4 months postintervention ($p < 0.001$, $d = 2.38$), with a large effect size. The intragroup differences are shown in Table 3.

Perfect positions. In terms of the left hand, the ANOVA revealed significant changes during group × time ($F = 4.89$, $p = 0.001$, $\eta_p^2 = 0.189$) and time ($F = 19.13$, $p < 0.001$, $\eta_p^2 = 0.313$). The post hoc analysis showed that both the MI and AO groups showed statistically significant differences compared with the PO group postintervention ($p < 0.001$; $d = 3.50$ and $d = 5.61$, respectively), 1 week postintervention ($p < 0.001$; $d = 2.09$ and $d = 5.59$, respectively) and 1 month postintervention ($p < 0.01$; $d = 1.44$ and $d = 3.60$, respectively), with a large effect size. However, only the AO group showed significant differences compared with the PO group at 4 months postintervention, with a large effect size ($p < 0.001$, $d = 2.32$). The AO group was also superior to the MI group at 1 week ($p = 0.027$, $d = 0.88$), 1 month ($p = 0.001$, $d = 1.29$) and 4 months ($p = 0.003$, $d = 1.09$) postintervention, with a large effect size. However, there were no differences between the two mental practice groups postintervention ($p > 0.05$). The intragroup differences are summarized in Table 4.

In terms of the right hand, the ANOVA revealed significant changes during time ($F = 15.05$, $p < 0.001$, $\eta_p^2 = 0.264$) but not during group × time ($F = 1.33$, $p = 0.248$, $\eta_p^2 = 0.06$). The post hoc analysis showed that the MI and AO groups showed statistically significant differences compared with the PO group at all assessment times, with a large effect size ($p < 0.01$, $d > 0.8$). The AO group was also superior to the MI group postintervention ($p = 0.048$, $d = 0.87$), 1 month postintervention ($p = 0.012$, $d = 0.81$) and 4 months postintervention ($p < 0.001$, $d = 1.49$), with a large effect size. However, there were no differences between the MI and AO groups at 1 week postintervention ($p > 0.05$). The intragroup differences are summarized in Table 4.

In terms of both hands, the ANOVA revealed significant changes during group × time ($F = 5.60$, $p < 0.001$, $\eta_p^2 = 0.211$) and time ($F = 27.37$, $p < 0.001$, $\eta_p^2 = 0.395$). The post hoc analysis showed that the MI and AO groups showed statistically significant differences compared with the PO group postintervention ($p < 0.01$; $d = 1.30$ and $d = 4.74$, respectively), 1 week postintervention ($p < 0.001$; $d = 1.74$ and $d = 4.85$, respectively) and 1 month postintervention ($p < 0.01$; $d = 1.23$ and $d = 4.02$, respectively), with a large effect size. However, only the AO group showed significant differences compared with the PO group 4 months postintervention, with a large effect size ($p < 0.001$, $d = 2.11$). The AO group was also superior to the MI group postintervention ($p < 0.001$, $d = 1.36$), 1 week postintervention ($p < 0.001$, $d = 1.36$) and 1 month postintervention ($p = 0.012$, $d = 1.29$), with a large effect size. However, there were no significant differences 4 months postintervention between the MI and AO groups ($p > 0.05$) (Fig. 2). The intragroup differences are summarized in Table 4.

Analysis according to the ability to imagine movements. In the MI group, based on the median score achieved in the MIQ-R questionnaire (Md = 50 points), the participants were classified into "good imagers" (those above median; n = 8) or "poor imagers" (those below median; n = 7).

Measure	Group	Mean ± SD				Mean difference (95% CI); effect size (d) (a) post—1 week (b) post—1 month (c) post—4 months
		Post	1 week	1 month	4 months	
Left hand	PO	11.6 ± 20.8	10.0 ± 15.8	8.3 ± 15.4	5.0 ± 10.3	(a) 1.6 (− 12.9 to 16.2); $d=0.08$ (b) 3.3 (− 17.7 to 24.4); $d=0.18$ (c) 6.6 (− 16.8 to 30.1); $d=0.40$
	MI	88.3 ± 22.8	66.6 ± 34.9	48.3 ± 35.9	30.0 ± 33.0	(a) 21.6* (7.0 to 36.2); $d=0.73$ (b) 40.0** (18.8 to 61.1); $d=1.33$ (c) 58.3** (34.8 to 81.8); $d=2.05$
	AO	98.3 ± 6.4	90.0 ± 12.6	90.0 ± 28.0	68.3 ± 37.1	(a) 8.3 (− 6.2 to 22.9); $d=0.83$ (b) 8.3 (− 12.7 to 29.4); $d=0.40$ (c) 30.0* (6.5 to 53.5); $d=1.12$
Right hand	PO	18.3 ± 29.0	18.3 ± 27.5	11.6 ± 15.9	0.0 ± 0.0	(a) 0.0 (− 12.7 to 12.7); $d=0$ (b) 6.6 (− 11.2 to 24.6); $d=0.28$ (c) 18.3 (− 2.9 to 36.6); $d=0.89$
	MI	58.3 ± 44.9	60.0 ± 36.3	51.6 ± 39.5	26.6 ± 34.6	(a) − 1.6 (− 14.4 to 11.0); $d=-0.04$ (b) 6.6 (− 5.5 to 14.6); $d=0.15$ (c) 31.6*(10.4 to 52.9); $d=0.79$
	AO	88.3 ± 18.6	83.3 ± 18.1	83.3 ± 24.4	73.3 ± 27.5	(a) 5.0 (− 7.7 to 17.7); $d=0.27$ (b) 5.0 (− 12.9 to 22.9); $d=0.23$ (c) 15.0 (− 6.2 to 36.2); $d=0.63$
Both hands	PO	10.0 ± 15.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	(a) 10.0 (− 3.9 to 23.9); $d=0.89$ (b) 10.0 (− 6.6 to 26.6); $d=0.89$ (c) 10.0 (− 6.4 to 26.4); $d=0.89$
	MI	46.6 ± 36.4	40.0 ± 32.4	30.0 ± 34.3	23.3 ± 34.6	(a) 6.6 (− 7.2 to 20.5); $d=0.19$ (b) 16.6* (0.5 to 33.2); $d=0.46$ (c) 23.3* (6.9 to 39.7); $d=0.65$
	AO	85.0 ± 15.8	78.3 ± 22.8	68.3 ± 24.0	41.6 ± 27.8	(a) 6.6 (− 7.2 to 20.5); $d=0.34$ (b) 16.7* (0.5 to 33.3); $d=0.82$ (c) 43.3** (26.9 to 59.7); $d=1.91$

Table 4. Intragroup differences in perfect positions (%) outcome measure. *$p<0.05$; **$p<0.001$. *AO* action observation group, *CI* confidence interval, *m* month, *MI* motor imagery group, *PO* placebo observation group, *SD* standard deviation, *w* week.

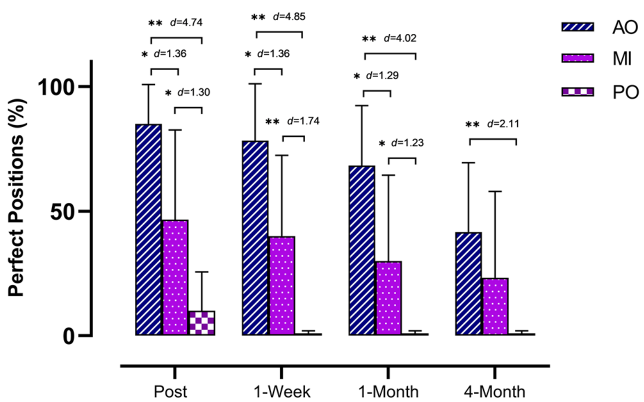

Figure 2. Between-group differences in perfect positions (%) outcome measure regarding bimanual gestures. *$p<0.05$; **$p<0.001$; *AO* action observation, *MI* motor imagery, *PO* placebo observation group, *d* d of Cohen.

Accuracy. Regarding the left hand, the ANOVA revealed significant changes during time ($F=7.71$, $p=0.005$, $\eta_p^2=0.68$) but not in group × time interaction ($F=2.04$, $p=0.166$, $\eta_p^2=0.358$).

For the right hand, the ANOVA revealed significant changes during time ($F=9.82$, $p=0.002$, $\eta_p^2=0.728$) but not in group × time interaction ($F=2.83$, $p=0.087$, $\eta_p^2=0.436$).

Finally, regarding both hands, the ANOVA revealed significant changes during time ($F=4.41$, $p=0.029$, $\eta_p^2=0.546$) but not in group × time interaction ($F=0.217$, $p=0.883$, $\eta_p^2=0.056$).

Time required. Regarding the left hand, the ANOVA revealed significant changes during time ($F=5.78$, $p=0.013$, $\eta_p^2=0.61$) but not in group × time interaction ($F=0.876$, $p=0.483$, $\eta_p^2=0.193$).

In relation to the right hand, the ANOVA did not reveal significant changes during time ($F=1.60$, $p=0.245$, $\eta_p^2=0.303$) and not in group × time interaction ($F=0.43$, $p=0.74$, $\eta_p^2=0.105$).

For both hands, the ANOVA revealed significant changes during time ($F=4.23$, $p=0.032$, $\eta_p^2=0.535$) but not in group × time interaction ($F=3.11$, $p=0.071$, $\eta_p^2=0.459$).

Perfect positioning. Regarding left hand, the ANOVA revealed significant changes during time ($F=9.61$, $p=0.002$, $\eta_p^2=0.724$) but not in group × time interaction ($F=2.86$, $p=0.085$, $\eta_p^2=0.439$).

For the right hand, the ANOVA revealed significant changes during time ($F=6.6$, $p=0.001$, $\eta_p^2=0.43$) but not in group × time interaction ($F=1.82$, $p=0.18$, $\eta_p^2=0.738$).

Finally, regarding both hands, the ANOVA revealed significant changes during time ($F=4.53$, $p=0.02$, $\eta_p^2=0.545$) but not in group × time interaction ($F=2.21$, $p=0.011$, $\eta_p^2=0.559$).

Action observation and placebo group. The ANOVA revealed no difference in time or group × time interaction for either hand or any of the variables. The median score for each group was Md = 52 for the AO group, and Md = 51 for de PO group.

Discussion

The primary objective of the present study was to assess the short to medium-term impact of MI and AO in isolation on the motor learning of a sequence of thumb-opposition tasks of increasing complexity in terms of accuracy compared with a placebo intervention. The secondary objectives were to evaluate the required time and the percentage of perfect positions. In addition, we also aimed to assess the effects on motor learning based on the ability to imagine movements in order to verify whether good imagers showed greater benefits than poor imagers accordingly to each intervention.

The results of the present study showed that the AO group had significantly higher accuracy than the MI or PO group until at least 4 months after the mental practice intervention in isolation, an aspect that had not been shown in scientific literature until these results. In the study by Gatti et al.[15] only one intervention session was performed; thus, only the rapid phase of the motor learning process was applied. The study participants had to learn a complex and unusual motor task that involved moving the right hand and foot in the same angular direction, while simultaneously moving the left hand and foot in an opposite angular direction. The authors employed a kinematics analysis to assess the motor learning process, the results of which are in line with those of our study, i.e., the authors found that AO was more effective than MI. González-Rosa et al.[16] also found that AO was more effective than MI in promoting the early learning of a new complex coordination task. In patients with chronic neck pain, Cuenca-Martínez et al.[34] showed that AO intervention in isolation showed the strongest results improving cervical joint position sense in comparison with MI and placebo group.

The results of the present study support these findings and show that AO is more effective than MI in motor learning until at least 4 months after the motor training session for unimanual motor positions and until at least 1 month later in the bimanual positions. It would have been interesting to conduct neuroimaging studies to evaluate the neurophysiological functional connections caused by brain training and motor learning.

These studies focused on the study of motor learning through the movement representation techniques in isolation. However, several studies have evaluated the effect of mental practice in combination with physical practice to also evaluate the process of motor learning. For example, Cuenca-Martínez et al.[35] found that AO plus physical practice caused faster changes in lumbopelvic motor control compared with only physical practice but not, in comparison with MI plus physical practice in asymptomatic participants. In fact, it seems that combining mental practice and physical practice is likely to minimize the differences between the two movement representation techniques (MI and AO). We did not enter differences between AO and MI groups either by adding physical practice with respect to improving strength[36].

In terms of the time required, the results showed that the MI group required significantly more time than the PO and AO groups to remember and perform the left-hand and two-handed gestures. At this point, the question becomes, why does AO show different results than MI? Gatti et al.[15] have argued that AO has a greater impact than MI due to several factors. First, the mirror neuron system functions more accurately and adequately through observation. For example, the ventral premotor cortex, an area widely involved in the planning of voluntary movement, receives afferences from the visual cortex. AO might therefore cause greater neurophysiological functional activation than imagination does.

The relationship between learning and required time has been extensively explored in the literature. Some models in this regard have found an increase in the speed of task execution as a skill learning is consolidated, which could explain the results in favor of the AO group[37]. However, a surprising result is that the PO group took less required time to perform the gesture, although they made many more mistakes. In that sense, some studies have shown that people with a lower skill may have a higher frustration when executing the task, as well as a lower motivation, which leads them not to take the task seriously, and may explain the lower time spent on it[38].

In addition, the act of imagining can vary among individuals and could therefore be related to associated variables such as the physical activity level, the ability to imagine movements, the complexity of the task to be imagined, the time spent imagining, the effort required for the task and the vividness and controllability of the image[8,36–39]. Therefore, although the AO group had an exact, precise, unambiguous, and specific reference model for the required motor positions, the MI group had only its own capacity to imagine movements to perform the brain training, so the insufficient mental engagement could be possible in MI group. This fact could also be relevant in explaining the findings of this study.

We also hypothesize that fatigue due to MI is another possible factor explaining the observed differences. Roure et al.[43] and Guillot et al.[44] have reported that mental practice causes mental fatigue and difficulty maintaining attention. Future research should compare different MI dosages to assess effects with respect to AO training but always monitoring fatigue because it can be an important physical condition to take into consideration. The loss of attention might therefore be greater in the MI group than in the AO group, which could be an important variable in motor learning. Buccino[12] argued that MI has certain intrinsic limits that AO does not exhibit because MI is a more demanding tool than AO in terms of attention and concentration. This argument agrees with the hypotheses proposed in the present study in the comparison between the two sensorimotor neuro-training tools.

Regarding the aimed to assess the effects on motor learning based on the ability to imagine movements, one of the most interesting hypotheses is whether participants with greater ability to perform mental motor images can obtain more benefits from the intervention, especially from MI. However, the results of this analysis showed no difference between "good imagers" and "poor imagers" in terms of accuracy, time required or totally correct positions.

Previous studies have shown greater benefits in MI in subjects with greater ability to imagine movements, such as Robin et al.[8], in relation to motor performance in a specific tennis gesture. However, it is necessary to highlight that all the participants of our study presented high levels to imagine movements, especially in a kinesthetic manner. It is possible that both groups (better and poorer imagers) had a good ability to imagine movements, which could explain the absence between-groups differences.

Potential applications. We analyzed the study's results a theoretical viewpoint and a from a functional viewpoint and from. In terms of functionality, the assessment 1 week postintervention has greater importance. In light of the results of the more complex tasks for the perfect positions, AO was better than MI; however, AO was not superior in terms of accuracy. From a theoretical viewpoint and to answer the question, "which mental practice tool in isolation has a greater and more lasting potential in motor learning?", it appears that AO training is superior to MI with minimal training. However, it would be interesting to perform this theoretical comparison by training the motor imagery group beforehand or by increasing the intervention load.

From a functional point of view, AO could be employed both in isolation and in combination with real practice to learn gestures and motor positions widely demanded in several fields, such as music (position of chords or notes), sport (gestures, grips, skill acquisition), neurorehabilitation, improvement of surgical techniques and in communication processes such as sign language, which uses fixed manual positions for word exchange. In addition, tools such as AO can enable a motor learning (or relearning) process and maintain it over time and can have a clinical effect on patients who, for whatever reason (e.g., surgery, immobilization.), cannot move in real-time and should be employed to improve patient outcomes. MI could also be used but it appears that the effect is significantly less than AO training. However, the main advantage of MI is that scenarios can be changed and adapted to the patient's context.

Limitations. This study presents several limitations. First, an important objective of the present study was to observe the differences between mental practice groups with a minimal intervention. However, Hinshaw[45] argued that the optimal time for obtaining the greatest benefits with MI is between 10 and 15 min. In the present study, the duration of the MI intervention was shorter, which might have been insufficient to obtain the full potential of MI. Second, AO and MI techniques, although sharing a large network of neurophysiological activity, these are not the same. During AO training, dependent areas of the visual cortex are activated with greater intensity compared with MI in a kinesthetic manner. However kinesthetic MI includes a greater component of somatosensory stimulation such as the dorsal column-medial lemniscus pathway. It would have been very interesting, and this should be considered a major limitation, to include a fourth group that only performed visual MI to be able to compare with AO because of their convergence in the neurophysiology underlying both techniques. Third, we did not evaluate the perceived fatigue, which could have been an interesting variable for explaining the results of the present study. Fourth, it would have been interesting to evaluate the autonomic variables during training to evaluate mental effort indirectly, especially in the MI group. Fifth, we did not measure the participants' perceived difficulty in learning each gesture nor the vividness of the intervention. The relationship between these variables and the study's results would have been interesting to know. Sixth, the AO group showed a greater ability to imagine movements visually than the other groups, which should be taken into account. Seventh, it was not possible to control the intervention to the participants during the follow up, so it is not possible to state categorically that everyone performed the task and learning adequately, which could influence the differences found. Finally, we could have used more functional motor gestures than just thumb to finger-opposition tasks to operationalize motor learning.

Conclusions

Based on the results obtained, AO training was superior to MI until at least 4 months postintervention in terms of accuracy and perfect positions for the unimanual gestures, and until at least 1 month postintervention in terms of perfect positions for the bimanual gestures. However, in terms of accuracy for the bimanual gestures, AO was not superior to MI at only 1 week postintervention. The AO group also required less time than the MI group to remember and perform the manual positions. Both AO and MI were superior to the placebo intervention until at least 1 month postintervention, and only AO was superior at 4 months. MI was never superior to AO training. Finally, "good imagers" did not obtain any better results than the "poor imagers" on any outcome measure in this study probably because all participants had a high ability to imagine movements. AO could be employed to learn gestures and motor positions, so could be a useful tool for enable a motor learning in the short to medium-term. MI could also be used but it appears that the effect is significantly less than AO training.

Data availability

Study data is available upon request from the authors.

Received: 3 October 2019; Accepted: 16 June 2020
Published online: 23 July 2020

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Acknowledgements
We thank Mª José Martínez Cremades for her help with sample collection and La Salle University Center for Advanced Studies for making this study possible, as well as all the participants in this study. This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sector.

Author contributions
F.C.M. applicated the interventions and wrote the main manuscript text. F.C.M. and R.L. assisted with the writing of the manuscript and analysed the data. L.S.M. and J.L.H. assisted with the acquisition of data. All authors contributed to the conception and design of the study and reviewed the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41598-020-67905-7.

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brain sciences

Review

The Role of Movement Representation Techniques in the Motor Learning Process: A Neurophysiological Hypothesis and a Narrative Review

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Received: 22 November 2019; Accepted: 30 December 2019; Published: 2 January 2020

Abstract: We present a neurophysiological hypothesis for the role of motor imagery (MI) and action observation (AO) training in the motor learning process. The effects of movement representation in the brain and those of the cortical–subcortical networks related to planning, executing, adjusting, and automating real movements share a similar neurophysiological activity. Coupled with the influence of certain variables related to the movement representation process, this neurophysiological activity is a key component of the present hypothesis. These variables can be classified into four domains: physical, cognitive–evaluative, motivational–emotional, and direct-modulation. The neurophysiological activity underlying the creation and consolidation of mnemonic representations of motor gestures as a prerequisite to motor learning might differ between AO and MI. Together with variations in cognitive loads, these differences might explain the differing results in motor learning. The mirror neuron system appears to function more efficiently through AO training than MI, and AO is less demanding in terms of cognitive load than MI. AO might be less susceptible to the influence of variables related to movement representation.

Keywords: movement representation; motor learning; motor imagery; action observation; neurophysiological hypotheses; mirror neuron system

1. Introduction

Movement representation training represents a revolution in the field of cognitive neuroscience and in experimental and sports psychology owing to its potential in various fields of study [1,2]. Motor imagery (MI) and action observation training (AO) are two of the most widely studied movement representation techniques. MI is defined as a cognitive and dynamic ability involving the cerebral representation of an action, without its real motor execution [3]. AO training is considered as the internal representation of a set of movements evoked by the observer during live visualization of the movements [4].

These movement representation techniques (both in isolation [5,6], in conjunction with various movement representation modalities [7], and in combination with real practice [8,9]) can lead to acquisition of motor gestures. It is important to evaluate what happens when movement representation techniques are applied to motor gestures and to offer a set of arguments as to why this happens. Advances in neuroimaging studies have helped answer some of the most pressing questions.

In this regard, Grush in 2004 [10] proposed one of the most relevant theories in this field, the emulation theory of representation. This theory tries to establish a theoretical framework in which, during IM, the brain constructs a visual model between the body and the environment. Subsequently, these models produce or direct an efferent sensorimotor copy in order to provide expectations or predictions of sensory feedback. These models can also be run later to create new motor images, predict results of different actions, or build new motor plans. This is the reason that visual perception is the result of using this type of model to create expectations and interpret sensory contributions during MI. In this sense, AO could provide that visual input between the subject's body and the environment, which could facilitate the process of constructing the mental image [10].

On the other hand, Glover & Baran [11] have developed the motor–cognitive model of the MI. This model argues that central executive functions play a fundamental role during IM, but not so much in open actions. In this model, it is shown that the creation of motor mental images involves both a planning phase and a movement execution phase. To begin the creation of the mental image for the preparation of movement, an initial mental image is generated based on the motor representations stored in the nervous system. During MI and real execution, neurologically, the processes are very similar, but nevertheless, during the execution of the mental task and the execution of the real task, the processes change remarkably. During real movement, the nervous system unconsciously accesses processes of visual and proprioceptive feedback to refine the movement simultaneously with its execution. However, during MI, the control of movement creation is consciously dependent on the initial image created. That is why the ability to create motor mental images depends on the fidelity in which the subject can create the initial image. The widely developed motor actions are going to suppose a lower cognitive demand and a greater reliability in the representation, and on the contrary, the poor developed actions could create an unreliable and unprecise motor images [11].

However, despite variations in nomenclature, there are at least three established and widely described phases in the process of acquiring new motor gestures [12]. The first phase is the cognitive, characterized by the presentation of a novel gesture and the process of cognitive capture, wherein relevant information is gathered to form strategies to respond to the new demands. This phase includes an information gathering stage and a configuration of movement representation (i.e., the image of the motor gesture is constructed) [12].

The next two phases are the associative and automatic [12], where the motor gesture is practiced in sequences as simple as possible, until the gesture has been integrated and automated. The cognitive load is gradually reduced [13] by the action of subcortical neurophysiological structures, ultimately enabling the motor gesture to be simultaneously performed with other movements. In addition to this, it is important to stress that the repertory of motor gestures can be learned through an exploratory process. Above all, novel motor gestures. The feedback mechanism can help the learning process, as, for example, having knowledge of mistakes can consolidate the improved acquisition of a given motor gesture. Several authors have investigated the importance of feedback in motor learning process [14–16].

There are similarities and differences between physical practice and movement representation techniques. Therefore, the main objective of this hypothesis was to present a set of neurophysiological aspects that are likely to be involved in the motor learning process and that are mediated by MI and AO training. The secondary objective was to formulate a hypothesis to explain the differences in the effects on motor learning between AO and MI.

2. Effectiveness of AO and MI in the Motor Learning Process: A Minireview

Prior to the formulation of this hypothesis, a literature search was conducted to analyze whether MI and AO were effective in the process of acquiring new motor gestures. It is therefore that a minireview was carried out, which had as its main objective to see if both techniques of motion representation work in the process of motor learning.

Regarding the search strategy, the search for scientific articles was performed using PubMed (2014 to December 2019, 16th). The specific search strategy used for the database is shown below: ((((((((((("motor"[All Fields] OR "motor's"[All Fields]) OR "motoric"[All Fields]) OR "motorically"[All Fields]) OR "motorics"[All Fields]) OR "motoring"[All Fields]) OR "motorisation"[All Fields]) OR "motorised"[All Fields]) OR "motorization"[All Fields]) OR "motorized"[All Fields]) OR "motors"[All Fields]) AND (((("imageries"[All Fields] OR "imagery psychotherapy"[MeSH Terms]) OR ("imagery"[All Fields] AND "psychotherapy"[All Fields])) OR "imagery psychotherapy"[All Fields]) OR "imagery"[All Fields])) OR ((("action"[All Fields] OR "action's"[All Fields]) OR "actions"[All Fields]) AND (((((((((((((("observability"[All Fields] OR "observable"[All Fields]) OR "observables"[All Fields]) OR "observation"[MeSH Terms]) OR "observation"[All Fields]) OR "observe"[All Fields]) OR "observed"[All Fields]) OR "observer"[All Fields]) OR "observer's"[All Fields]) OR "observers"[All Fields]) OR "observes"[All Fields]) OR "observing"[All Fields]) OR "watchful waiting"[MeSH Terms]) OR ("watchful"[All Fields] AND "waiting"[All Fields])) OR "watchful waiting"[All Fields]) OR "observations"[All Fields]))) AND ((((((((((("motor"[All Fields] OR "motor's"[All Fields]) OR "motoric"[All Fields]) OR "motorically"[All Fields]) OR "motorics"[All Fields]) OR "motoring"[All Fields]) OR "motorisation"[All Fields]) OR "motorised"[All Fields]) OR "motorization"[All Fields]) OR "motorized"[All Fields]) OR "motors"[All Fields]) AND (((((("learning"[MeSH Terms] OR "learning"[All Fields]) OR "learn"[All Fields]) OR "learned"[All Fields]) OR "learning's"[All Fields]) OR "learnings"[All Fields]) OR "learns"[All Fields])). (Filters: Randomized Controlled Trials, from 2014–2019).

With respect to the inclusion criteria, the selection criteria used in this review were based on methodological and clinical factors, such as the population, intervention, control, outcomes, and study design (PICOS) [17] criteria as follows:

Population: both healthy subjects and patients with any type of clinical entity susceptible to motor learning. Intervention and control: the intervention must contain at least one of the two movement representation techniques (MI or AO) in isolation or in combination with physical practice. For comparison, any other intervention different from the movement representation techniques or physical practice in isolation. Outcomes: any variable with the objective of evaluating the learning or re-learning of motor gestures. Finally, the study design: randomized controlled trials were selected. Only studies published in the last five years were considered.

The assessment of the methodological quality of the studies was performed using the PEDro list [18]. The PEDro scale assesses the internal and external validity of a study and consists of 11 criteria: (1) specified study eligibility criteria, (2) random allocation of subjects, (3) concealed allocation, (4) measure of similarity between groups at baseline, (5) subject blinding, (6) therapist blinding, (7) assessor blinding, (8) fewer than 15% dropouts, (9) intention-to-treat analysis, (10) between-group statistical comparisons, and (11) point measures and variability data. Criteria (2)–(11) were used to calculate the PEDro score. The methodological criteria were scored as follows: yes (one point), no (zero points), or do not know (zero points). The PEDro score of each selected study provided an indicator of the methodological quality (9–10 = excellent; 6–8 = good; 4–5 = fair [18].

Two independent reviewers examined the quality of the studies selected using the same methods, and disagreements between reviewers were resolved by consensus including a third reviewer. The inter-rater reliability was determined using the Kappa coefficient, where >0.7 indicated a high level of agreement between assessors, between 0.5 and 0.7 indicated a moderate level of agreement, and <0.5 indicated a low level of agreement [19].

Regarding the results, Table 1 summarizes the results of the included studies. The total number of articles found was 21. Five studies addressed patients and 16 healthy subjects. Table 2 summarizes the methodological quality. The inter-rater reliability of the methodological quality assessment was high (k = 0.755). With respect to the studies included, the average score was 5.1 ± 1.54. Six studies showed good quality and 15 showed fair quality.

To conclude this part of the manuscript, the studies of this minireview showed that movement representation techniques in both patients and healthy subjects improve the results of physical practice in isolation. Therefore, for the process of acquiring new motor gestures, physical practice should be combined with movement representation techniques to obtain better results.

Table 1. Characteristics of the included studies.

Trial	Population (Patients)	Intervention Data and Target	Results
Cabral-Sequeira et al. 2016 [20]	Adolescents with cerebral palsy: 11- to 16-year-old participants (mean = 13.58 years), who suffered left (*n* = 16) or right (*n* = 15) mild hemiparesis.	EG: Day 1: MI in isolation Day 2: MI plus physical training on motor learning an aiming task CG: Day 1: recreational activities Day 2: physical training on motor learning an aiming task.	MI increased motor learning as a function of side hemiparesis in comparison with a no MI intervention.
Kumar et al. 2016 [21]	Ambulant stroke subjects: 40 hemi paretic subjects (>3 months post-stroke) who were ambulant with good imagery ability.	EG (*n* = 20): task-oriented training group plus MI CG (*n* = 20): task-oriented training group in paretic lower extremity muscles strength and gait performance.	Additional task specific MI training improves paretic muscle strength and gait performance in ambulant stroke patients.
Keynen et al. 2018 [22]	Stroke patients: 56 patients with a stroke (>3 months ago), capacity to walk independently with or without a walking aid over 10 m (with a self-selected gait speed <1.2 m/s), and presence of hemiparesis (indicated by a score of <100 on the lower extremity part of the Motricity	AO group (*n* = 20) Analogy instruction (*n* = 19) Environmental group (*n* = 17) To explore immediate changes in walking performance when using the three implicit learning.	Analogy instructions and environmental constraints can lead to specific, immediate changes in the walking performance and were in general experienced as feasible by the participants.

	Index and a score <34 on the lower extremity part of the Brunnstrom Fugl–Meyer assessment).		
La Touche et al. 2019 [9]	Patients with chronic non-specific low back pain: (low back pain for at least the prior three months; low back pain of nonspecific nature).	MI plus physical training (n = 16) Tactile feedback plus physical training (n = 16) CG: physical training in isolation (n = 16). Motor control gestures acquisition.	The MI strategy was the most effective mode for developing the motor control task in an accurate and controlled manner, obtaining better outcomes than tactile feedback or verbal instruction.
Moukarzel et al. 2019 [23]	Patients with total knee arthroplasty (n = 24). Four men and 20 women aged from 65 to 75 years (70 ± 2.89).	EG: MI plus physical therapy program (progressive lower-extremity strengthening exercises combined with electrical stimulation for quadriceps muscle, manual therapy, knee proprioceptive exercises, gait training, and functional exercises on stairs (n = 12). CG: physical therapy program in isolation (n = 12). Quadriceps strength, peak knee flexion during the swing phase, performance at the timed up and go test, stair climbing test, six-minute walk test, and Oxford knee score.	MI showed effectiveness in gait performance and functional recovery in a small sample of patients with total knee arthroplasty.
Trial	**Population (Healthy Subjects)**	**Intervention Data and Target**	**Results**

Cuenca-Martínez et al. 2019 [24]	HS (*n* = 45). Fourteen men and 31 women aged from 18 to 65 years.	MI plus physical training program for the lumbo-pelvic region (*n* = 15) AO plus program for the lumbo-pelvic (*n* = 15) CG: physical training in isolation (*n* = 15). Lumbo-pelvic motor control gestures acquisition.	AO training caused faster changes in lumbo-pelvic motor control compared with the CG group. All groups showed within-group significant differences between pre- and post-intervention.
Bek et al. 2016 [25]	HS (*n* = 50). The imagery group (*n* = 18, 5 males) had a mean age of 19.4 ± .98 years, the attention group (*n* = 15, 2 males) had a mean age of 19.9 ± 1.4 years, and the control group (*n* = 17, 1 male) had a mean age of 19.8 ± 1.7 years.	Two blocks of trials were completed, and after the first block, participants were instructed to imagine performing the observed movement (imagery group, *n* = 18) or attend closely to the characteristics of the movement (attention group, *n* = 15), or received no further instructions (control group, *n* = 17). To improve imitation with imagery or attention	Both attention and motor imagery can increase the accuracy of imitation and have implications for motor learning and rehabilitation.
Sheahan et al. 2018 [26]	HS (*n* = 58). (36 females; 25.0 ± 4.1 years).	Group 1: Follow through (*n* = 8), Group 2: Planning only (*n* = 8), Group 3: MI (*n* = 16), Group 4: No motor imagery (*n* = 16), Group 5: Motor imagery no fixation (*n* = 8).	Results showed that simply imagining different future movements could enable the learning and expression of multiple motor skills executed over the same physical states.

		Motor gestures acquisition	When subjects performed the gesture and only imagined the follow-through, substantial learning occurred.
Dana & Gozalzadeh, 2017 [27]	Young male HS (*n* = 36) (15 to 18 years).	Internal MI plus physical practice (*n* = 12) External MI plus physical practice (*n* = 12) CG: no-imagery, mental math exercise plus physical practice (*n* = 12). The performance accuracy of the groups on the serve, forehand, and backhand strokes was measured.	Results showed significant increases in the performance accuracy of all three tennis strokes in all three groups, but serve accuracy in the internal imagery group and forehand accuracy in the external imagery group showed greater improvements, while backhand accuracy was similarly improved in all three groups.
Kim et al. 2017 [28]	HS (*n* = 40), novices.	Four groups: Action observation training (*n* = 10), Motor imagery training (*n* = 10), Physical practice (*n* = 10) and no practice (*n* = 10). Golf putting performance.	Results showed that the accuracy of the putting performance were improved over time through the two types of cognitive training (AO and MI training).
Gonzalez-Rosa et al. 2014 [29]	HS (*n* = 30), non-athletes, right-handed volunteers (17 females, 13 males, mean age 22.9 + 2.3 years).	Three groups: AO watched a video of the task (*n* = 9), MI had to imagine it (*n* = 12), and CG with a distracting computation task (*n* = 9).	AO showed better learning compared with MI, and also elicited a stronger activity of the sensorimotor cortex during training, resulting in a lower amount of

		Early learning of a complex four limb, hand-foot coordination task, and kinematic analysis.	cortical activation during task execution. During AO, subjects appear to process and collect sensory and motor information relevant to action in an effective and efficient manner, which allowed them to apply a series of decision making strategies appropriate to defining which movement sequence to perform, and activating control processes such as feed forward control during motor execution.
Hidalgo-Pérez et al. 2015 [30]	HS (n = 40) 24 men and 16 women aged from 18 to 65 years.	Group 1: MI plus motor control exercise (n = 20), Group 2: motor control exercise in isolation (n = 20). Sensorimotor function of the craniocervical region and the cervical kinesthetic sense.	Combining MI with the motor control exercise produced statistically significant changes in sensorimotor function variables of the craniocervical region. Cervical kinesthetic sense was not significantly different between both groups.
Ingram et al. 2016 [31]	HS (n = 102)	Four groups: MI or PP tested in either perceptual (altering the sensory cue) or motor (switching	Results suggested that MI-based training relies on both perceptual and motor learning, while PP-based

		the hand) transfer conditions (n = 60). CG (n = 42) that did not perform a transfer condition. Perceptual and motor learning through reaction time.	training relied more on motor processes.
Nishizawa & Kimura, 2017 [32]	HS females (n = 45) mean age 20.4 + 1.7 years).	Three groups: Model- and self-observation (n = 15), model-observation (n = 15), and self-observation (n = 15). Motor gesture learning through the acquisition of correct sports movement.	Observation combining model and self-observation exerted a positive effect on short-term motor gesture learning.
Kawasaki et al. 2018 [33]	Elderly HS (n = 36) aged 60 years or older (7 women and 29 men, mean age = 70.5 ± 6.19 years).	Three groups: Unskilled or skilled model observation groups (n = 12, respectively), or the CG (n = 12). Ball rotation performance (ball rotation speed).	Results indicated that the time taken for early phase learning of a finger coordination skill was improved when an unskilled model, rather than a skilled model, was used for AO combined with MI training.
Kraeutner et al. 2016 [34]	HS (n = 64) right-handed participants (42 female, 22.1 ± 5.3 years).	Two groups: MI in isolation (n = 31) Physical practice (n = 33) Implicit sequence learning task.	The magnitude of the learning did not differ between groups. It is suggested that MI and physical practice are equally effective in facilitating implicit sequence learning.

Kraeutner et al. 2017 [35]	HS (n = 72) Right-handed subjects (49 females, 23.8 ± 7.2 years)	Four conditions of MI-based practice: 4 training blocks with a high (4-High) or low (4-Low) sequence to noise ratio, or 2 training blocks with a high (2-High) or low (2-Low) sequence to noise ratio. Implicit sequence learning task.	Results showed that the extent to which implicit sequence learning occurs through MI is impacted by manipulations to entire training time and the sequence to noise ratio. In addition, results showed that the extent of implicit sequence learning occurring through MI is a function of exposure, indicating that like physical practice, the cognitive mechanisms of MI-based implicit sequence learning rely on the formation of stimulus response associations.
Lagravinese et al. 2016 [36]	HS (n = 25)	(AO) training: subjects were exposed to the observation of a video showing finger tapping movements executed at 3 Hz, a frequency higher than the spontaneous one (2 Hz) for four consecutive days. The changes in motor performance and motor resonance.	Results showed that multiple sessions of AO training induced a shift of the speed of execution of finger tapping movements toward the observed one and a change in motor resonance.
Lei et al. 2016 [37]	HS (n = 47) right-handed individuals (23 men, 17 women), aged from 18 to 30 years.	Five conditions:	Results showed an improvement in visuomotor adaptation following the action observation, as compared

		- AO, in which the subjects watched a video of a model who adapted to a novel visuomotor rotation - Proprioceptive training, in which the subject's arm was moved passively to target locations that were associated with desired trajectories - Combined training, in which the subjects watched the video of a model during a half of the session and experienced passive movements during the other half - Active training, in which the subjects adapted actively to the rotation - A control condition, in which the subjects did not perform any task.	with the adaptation performed by the individuals who were naïve to the given visuomotor rotation
Salfi et al. 2019 [38]	HS (n = 39) (aged 24.9 ± 3.0 years; range, 20–34; 18 males).	MI and Targeted memory reactivation. Four conditions: - MI in isolation - MI with an incompatible sound stimulation - AO	The combination of MI and targeted memory reactivation showed the largest early performance improvement, as indexed by the combined measure of speed and accuracy

		- Auditory targeted memory reactivation during AO To assess the influence on performance on a sequential finger tapping task of an auditory targeted memory reactivation during MI practice.	
Sobierajewicz et al. 2016 [39]	HS (n = 24) 6 males and 18 females range 21 to 28 years.	After an informative cue, a response sequence had either to be executed, imagined, or withheld. The learning of a fine hand motor gesture.	Both physical condition and MI condition improved the response time and accuracy although the effect of motor learning by motor imagery was smaller than the effect of physical practice

EG: experimental group, CG: control group, MI: motor imagery; AO: action observation; HS: healthy subjects, PP: physical practice.

Table 2. Assessment of the studies quality based on the PEDro scale.

	Items											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**
Cabral-Sequeira et al. 2016 [20]	~~1~~	1	0	1	0	0	0	1	0	1	1	**5**
Kumar et al. 2016 [21]	~~1~~	1	1	1	0	0	1	1	0	1	1	**7**
Keynen et al. 2018 [22]	~~1~~	1	1	1	0	0	0	1	0	0	1	**5**
La Touche et al. 2019 [9]	~~1~~	1	1	1	1	0	1	1	0	1	1	**8**
Moukarzel et al. 2019 [23]	~~1~~	1	0	1	1	0	1	1	0	1	1	**7**
Cuenca-Martínez et al. 2019 [24]	~~1~~	1	1	1	1	0	1	1	0	1	1	**8**
Bek et al. 2016 [25]	~~1~~	1	0	1	0	0	0	1	0	1	1	**5**
Sheahan et al. 2018 [26]	~~1~~	0	0	1	0	0	0	1	0	1	1	**4**
Dana & Gozalzadeh 2017 [27]	~~1~~	0	0	0	0	0	0	1	0	1	1	**3**
Kim et al. 2017 [28]	~~1~~	1	0	1	0	0	0	1	0	1	1	**5**
González-Rosa et al. 2014 [29]	~~1~~	1	0	1	0	0	0	1	0	1	1	**5**
Hidalgo-Pérez et al. 2015 [30]	~~1~~	1	1	1	0	0	1	1	0	1	1	**7**
Ingram et al. 2016 [31]	~~1~~	1	0	1	0	0	0	1	0	1	1	**5**
Nishizawa & Kimura, 2017 [32]	~~1~~	1	0	1	0	0	0	1	0	1	0	**4**
Kawasaki et al. 2018 [33]	~~1~~	1	1	1	0	0	0	1	0	1	1	**6**
Kraeutner et al. 2016 [34]	~~1~~	1	0	0	0	0	0	0	0	1	1	**4**
Kraeutner et al. 2017 [35]	~~1~~	1	0	1	0	0	0	0	0	1	1	**4**
Lagravinese et al. 2016 [36]	~~1~~	0	0	1	1	0	0	1	0	1	1	**5**
Lei et al. 2016 [37]	~~1~~	0	0	1	0	0	0	1	0	1	0	**3**
Salfi et al. 2019 [38]	~~1~~	0	0	1	0	0	0	1	0	1	1	**4**
Sobierajewicz et al. 2016 [39]	~~1~~	0	0	1	0	0	0	0	0	1	1	**3**

1: subject choice criteria are specified; 2: random assignment of subjects to groups; 3: hidden assignment; 4: groups were similar at baseline; 5: all subjects were blinded; 6: all therapists were blinded; 7: all evaluators were blinded; 8: measures of at least one of the key outcomes were obtained from more than 85% of baseline subjects; 9: intention-to-treat analysis was performed; 10: results from statistical comparisons between groups were reported for at least one key outcome; 11: the study provides point and variability measures for at least one key outcome.

3. Hypothesis

On the basis of the available body of evidence, we formulated a neurophysiological hypothesis regarding the potential role of movement representation techniques in the motor learning process. The components of this hypothesis are presented below.

3.1. Shared Neurophysiological Activity

There is congruence between the activity of the functional neuroanatomical networks of the cortical and subcortical areas related to the planning, execution, adjustment, and automation of real movement practice and the activity that occurs during mental movement representation. This process appears to be mediated by a common neural substrate.

3.2. Magnitude of Brain Activity

Greater neurophysiological congruence in sensorimotor networks results in greater learning than when lesser neurophysiological congruence has occurred. A greater magnitude of neurophysiological activity, produced through movement representation, would thus lead to greater motor learning compared with lower magnitude brain activity.

3.3. Influence of Variables Related to Movement Representation

The magnitude of the neurophysiological activation of cortical–subcortical sensorimotor networks related to movement planning, adjustment, and execution might be modulated by the influence of certain key variables. Our hypothesis is that MI is more susceptible than AO to the influence of these key variables, owing to the inherent characteristics of the motor image construction process.

In our hypothesis, there are four domains into which we can classify these key variables: the physical domain, the cognitive–evaluator domain, the motivational–emotional domain, and the direct modulation domain of the motor representation. Table 3 summarizes the main characteristics of these variables and their estimated effect on AO and MI.

We also propose a categorization system related to the influence of these variables on the process of movement representation. The primary variables are the direct modulation factors because they act directly on the process of live movement representation. Cognitive and physical variables could influence the direct modulation variables and the motor learning process. For example, physical activity levels could increase to generate more experience and thereby facilitate the generation of motor images. This process would also improve the understanding of the motor gesture, thereby facilitating the ability to perform the mental representation of movement. Motivational–emotional variables could influence all of these variables at all steps in the process. The visual information can help the creation of the motor representation and the set of direct modulation variables, as it can facilitate this process. This has been demonstrated in multiple studies [40–43]. The creation of the motor representation provokes a neurophysiological activation qualitatively similar to that occurring during physical practice. This has even been shown with neurovegetative activity [44]. The result of this process is the generation of mnemonic representations of movements as a prerequisite to motor learning. Figure 1 graphically represents this categorization system.

Table 3. Modulating variables of the movement representation process.

Domain	Variables	Influence
Physical **MI** *** **AO** *	- Levels of physical activity	- Greater physical activity levels might generate greater facility in constructing the movement due to the experience, development, and elaboration of habitual motor schemes.
	- Perceived of mental fatigue	- The presence of high fatigue levels can affect attention, thereby limiting the brain's construction of movement.
	- Disturbances in sensorimotor integration	- The presence of somatosensory disturbances can generate aberrant sensorimotor schemes that could affect the movement's construction, thereby leading to a decreased ability to generate motor images.
Cognitive–Evaluator **MI** *** **AO** *	- Understanding motor gestures and verbal instructions	- Understanding movements that are not physically elaborated can improve the planning phases of movement because emotional and cognitive limitations can be reduced.
	- Context	- The development of the movement in family and specific contexts could facilitate imagination and observation.
	- Functioning of the working memory	- Better functioning of the working memory could increase the ability to collect the provided information and its subsequent consolidation into long-term memory, thereby facilitating the motor learning process.
	- Self-efficacy levels	- Greater self-perception of the ability to generate motor images could enhance the brain's ability to construct motor images.
	- Attention levels	- Maintaining attention could facilitate the mental construction of movements and the total effort dedicated to that construction.
	- Expectations	- Expectations of the effects of movement representation techniques might influence the efficiency of the motor learning process.
	- Perception of difficulty	- Greater perception of the difficulty could lead to a reduced ability to generate motor representation and thereby worsen motor learning.

Motivational–Emotional **MI ***** **AO *****	- Motivation (reasons, intention, and desires)	- Higher motivation levels could lead directly to a better predisposition towards the learning process and, therefore, on the effects of movement representation techniques.
	- Fear of movement	- Higher kinesiophobia levels can lead to an interruption of the motion representation process, thereby impairing the motor learning process.
Direct modulation **MI ***** **AO ***	- Ability to create motor images	- The effectiveness of MI might depend on the ability to create motor images. This aspect can be influenced by other domains.
	- Synchronization	- Greater time congruence between physical practice and motion representation could facilitate the motor learning process.
	- Activity of the autonomous nervous system	- Greater neurovegetative activity could indicate higher neurophysiological activity of the sensoriomotor cortical–subcortical networks, indicating greater effort dedicated to the task, greater attention, and less fatigue, thereby favoring motor learning.

* low susceptibility; ** moderate susceptibility; *** high susceptibility. Abbreviations: AO, action observation; MI, motor imagery.

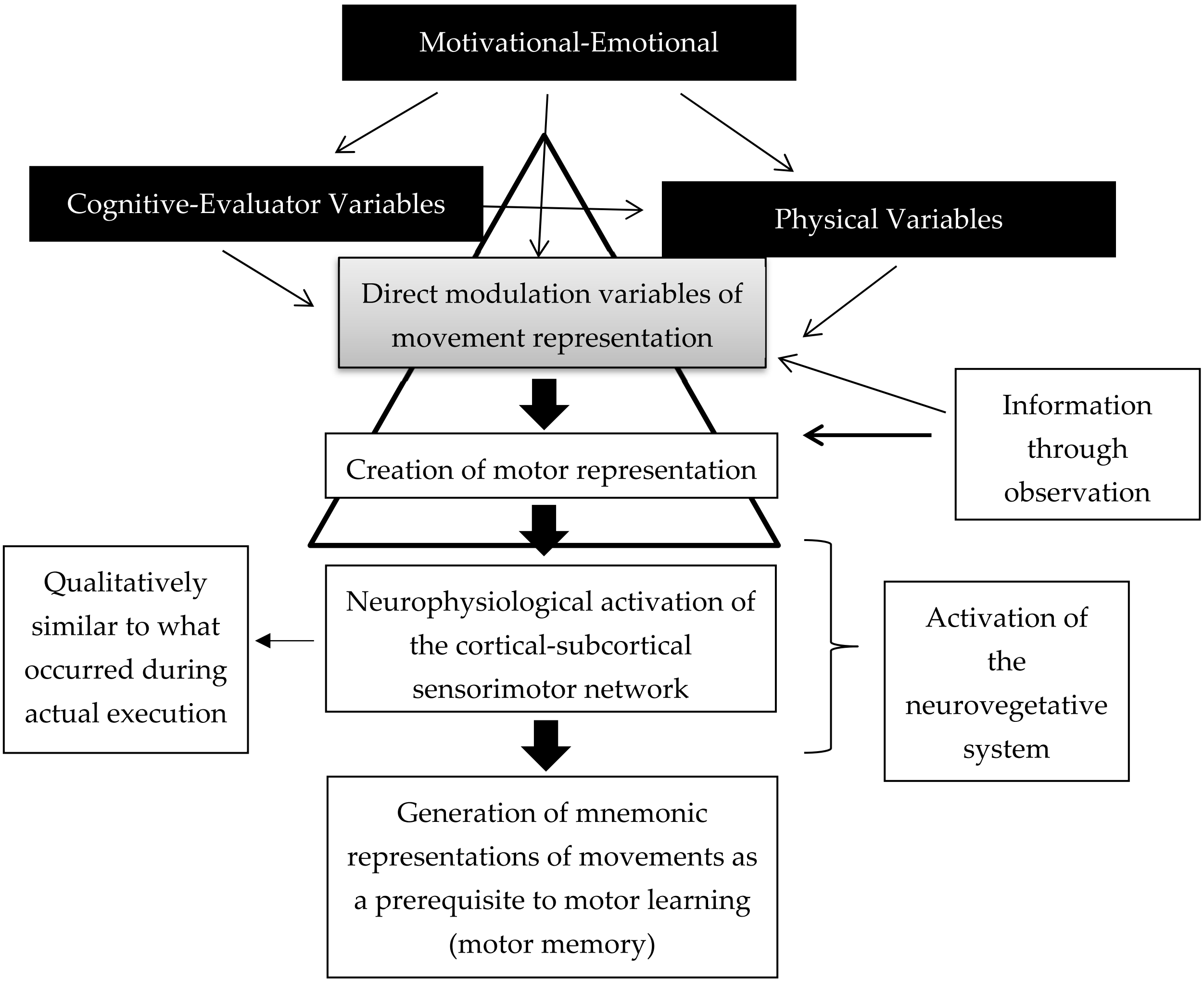

Figure 1. Neurophysiological view of the motor learning process mediated by movement representation techniques.

Several studies support the presence of these variables related to movement representation techniques. For example, regarding the cognitive variables, greater mental efforts made during imagery tasks led to greater hemodynamic changes at the cortical level [45]. Regarding the physical domain, there is extensive literature that supports their influence on the process of movement representation. For example, athletes with high levels of physical activity had a greater ability to generate motor images than amateur athletes with lower levels of physical activity [46–48]. The study conducted by La Touche et al. 2018 [49] showed that patients with chronic low back pain presented a negative correlation between the level of kinesiophobia and the ability to generate both kinesthetic and visual motor images. In addition, they also found that the ability to generate motor images was impaired in patients with chronic low-back pain compared with healthy participants. This also was found by another research group [50].

With respect to the direct modulation variables, providing visual input prior to performing an imagery motor task facilitates it and causes greater neurophysiological activity than if performed alone [42,43,51]. In addition, it has been found that the vividness of the imagination affected motor learning, showing more significant changes in those participants who presented a more vivid imagination [52]. Regarding the autonomic nervous system response, Cuenca-Martínez et al. [53] found that the complexity of movement, the effort-intensity, and the levels of physical activity can influence neurovegetative activity in the process of generating motor images. Finally, regarding the synchronization, several studies have showed that unknown, uncommon, and uncomfortable movements can lead to differences between the time employed between the imagined and real execution [54,55].

3.4. Differences in the Process of Creating Mnemonic Representations: Integration of Visual Information and Formation of Motor Memory

The cortical–subcortical neurophysiological activation that occurs during the representation of movements is likely to elicit the formation of specific and lasting memory imprints of the representations of the movements in the motor learning phases. Our hypothesis includes the following set of arguments regarding the creation of motor memory and the process of integrating visual information.

The first of these arguments is that the neurophysiological paths followed by the two movement representation tools (AO and MI) during the process of acquiring and integrating visual information differ. Therefore, different strategies are employed in the process of creating the motor print. The first argument introduces the second.

The second argument is that image construction through MI is likely fed initially by the continuous activity of the working memory, and then through the activity of the episodic buffer. Figure 2 shows how this operative memory activity acts in order to integrate the visual information feeding the image construction. However, Figure 2 also shows that image construction will also receive information from episodic memory. Episodic memory feeds and is fed by semantic memory and, in the same way, by perceptual memory. Therefore, MI requires predominantly conscious strategies for the image creation process, and thus a high cognitive load, which could explain the fatigue experienced during the image construction process through MI. However, it is important to stress that it is also possible to generate images relatively unconsciously on some occasions, such as during reading. However, MI predominantly needs conscious strategies.

The third argument is that AO is not necessarily dependent on the use of conscious strategies owing to the efficiency of externally provided images. In AO, the main task is to retain and understand the image rather than create it, facilitating the working memory tasks, and thus the construction of the motor print. As a result, image transformation and a conscious effort can occur during AO, but likely require less effort than for MI.

The fourth argument is that this neurophysiological activity is optimized between the central executive control (which is part of the working memory) and procedural memory, thereby enabling the acquisition of strategies, while being unaware of the processes that govern the acquisition of those strategies. Thus, during the process of creating the motor print through AO, there is likely to be greater involvement of implicit learning with the participation of the perceptive-motor procedural memory.

The fifth and last argument is that this activity could also respond to differences between AO and MI in susceptibility to the influence of physical, cognitive, motivational–emotional, and direct modulation variables, showing greater robustness for the influence of AO training (Figure 2).

3.5. Observing and Imagining: Different Cognitive Demands

The difference between MI and AO is that all participants have the same afferent visual information arriving for processing in AO, while in MI, even though everyone receives the same verbal instructions, it is likely that there are likely to be interindividual variations that could modulate the potential of MI, and consequently the effect of MI on learning. The success of MI depends mainly on each individual's ability to create motor images. It will also depend on the set of variables previously mentioned with the system of integration of somatosensory information, motivation, and levels of physical activity, among others.

Our hypothesis, therefore, is that the efficiency of the mirror neuron system is greater during AO training because the images are externally provided, whereas MI requires an internal, autonomous effort to create the images. This has been explicitly reported by Gatti et al. [56].

4. Theoretical Framework

On the basis of Finke's functional equivalence hypothesis [57], both forms of movement representation techniques lead to the activation of areas related to the planning, generation, and adjustment of voluntary movement at the neurophysiological level. These areas include the premotor cortex, supplementary motor cortex, primary motor cortex, primary somatosensory cortex, prefrontal cortex, posterior parietal cortex, thalamus, cerebellum, and basal ganglia. The areas are activated in a similar manner to when the action is physically performed. The actions of imagining, observing, and executing an action thus converge in similar motor representations [4,58–60].

This overlapping functional neuroanatomy between physical practice and motion representation is also similar in terms of the magnitude and volume of brain activation [61]. However, it has been reported that this activation is lower during movement representation than during physical practice [61], a finding also reported by Lacourse et al. 2005 [60], who suggested that these differences in neurophysiological activation could be the result of striatum overactivation during the movement representation process. An inhibitory mechanism of the corticospinal signal in this subcortical structure could be acting in parallel with a cortical–subcortical activation system during the process of creating the movement representation [60].

Lacourse et al. 2005 [60] also noted that one of the main differences between the physical and non-physical practice is the lack of sensorimotor feedback during movement representation, which could provoke inactivity of somatosensory processes supporting movement representation, resulting in an exclusively top-down process, thereby limiting the effectiveness of movement representation in motor learning. The term "top-down" refers to conceptually guided systems (i.e., they start from internal processes that construct and elicit a perceptual sensory output), while bottom-up processes refer to data-driven perceptual processes, where central processes function by receiving sensory data (i.e., they begin with sensory data and end with data interpretation) [62].

The time required to perform a certain action is similar to the time taken to represent that action as a motor image [63], even when contextual variations (such as placing weights on the arms) are included [64]. Studies have also found neurophysiological similarities in the neurovegetative responses to physical practice [65] and to movement representation [66,67], even with simple motor gestures [53].

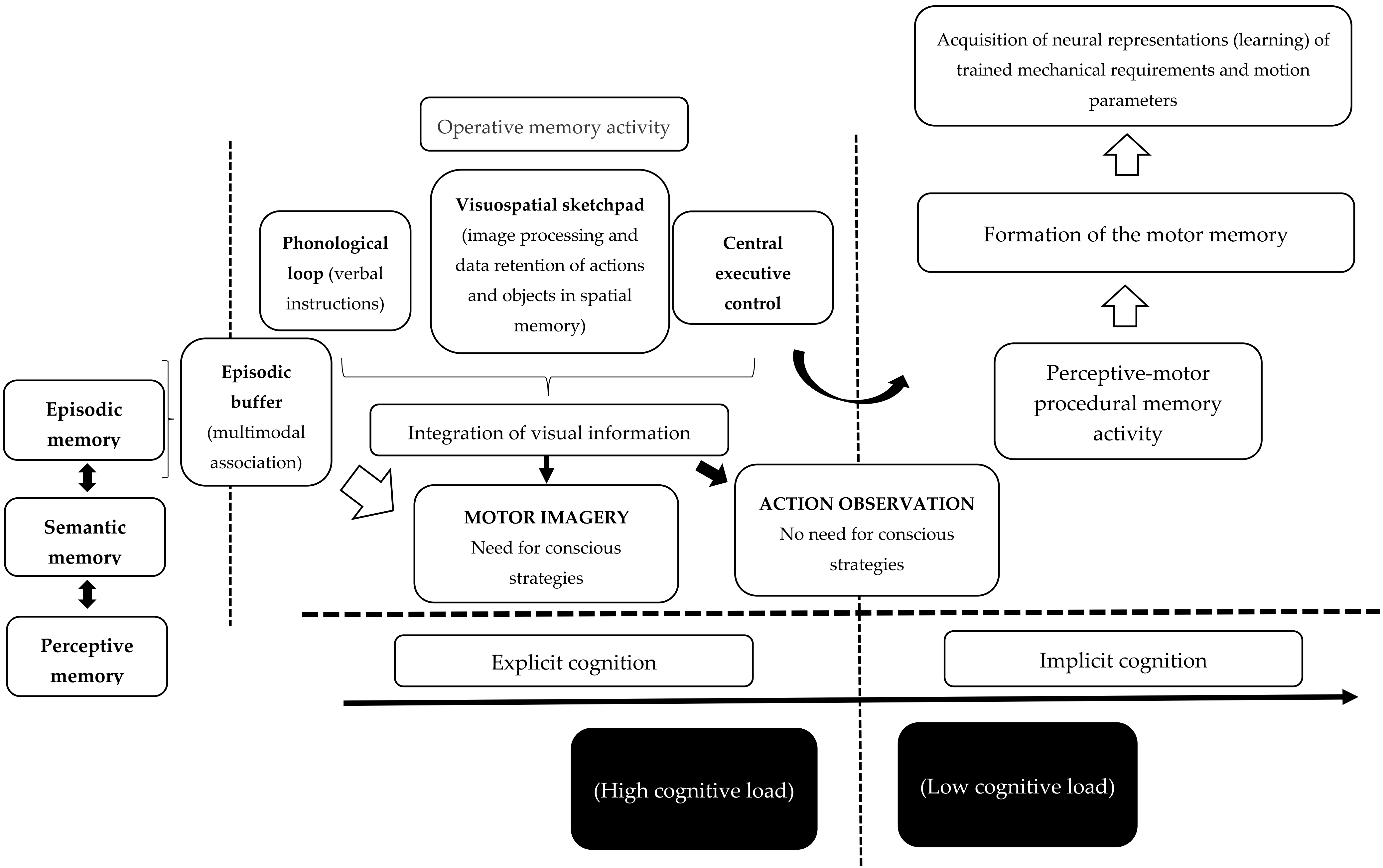
Acquisition of neural representations (learning) of trained mechanical requirements and motion parameters
Operative memory activity
Formation of the motor memory
Visuospatial sketchpad (image processing and data retention of actions and objects in spatial memory)
Phonological loop (verbal instructions)
Central executive control
Perceptive-motor procedural memory activity
Episodic memory
Episodic buffer (multimodal association)
Integration of visual information
Semantic memory
MOTOR IMAGERY Need for conscious strategies
ACTION OBSERVATION No need for conscious strategies
Perceptive memory
Explicit cognition
Implicit cognition
(High cognitive load)
(Low cognitive load)

Figure 2. Functioning and acquisition of mnemonic representations.

The functional relationship between movement representation and neurovegetative system activation could be based on an on-demand preparation phase (both qualitative and quantitative) of the musculoskeletal system (e.g., cardiorespiratory adaptations, sweating, body temperature adaptations) for upcoming energy expenditures [44,67].

Lacourse et al. 2005 [60] found that, after the acquisition of experience during the physical practice of a motor task and the evaluation of the movement representation process, there was no greater congruence of activation of the sensorimotor networks in comparison with physical practice than when the motor task was totally new. It has been found that the amplitude of the evoked motor potentials during AO and MI correlated positively with the ability to generate motor images [68]. Martin et al. 1990 [69] suggested that the ability to create motor images could determine the effectiveness of their use. These findings suggest that the ability to create movement representations could be a fundamental and primary modulator in the representation of motor gestures. This direct modulation, along with cognitive aspects such as understanding the motor gesture, would be present during the motor representation process. The combined physical and cognitive domains could directly influence the ability to generate motor mental images and indirectly affect motor learning. Lastly, there is the transversal motivational–emotional domain, which can influence all other domains, as well as MI and AO, owing to its effect on an individual's predisposition towards learning.

In an earlier study, La Touche et al. 2018 [49] found that the ability to generate motor images was impaired in patients with non-specific chronic low-back pain compared with healthy participants. Pijnenburg et al. 2015 [50] found that patients with chronic low-back pain showed a greater difference in the time performing a movement and the time spent on representing that movement. In addition, La Touche et al. 2018 [49] also found positive-moderate associations between an increased ability to create motor images and increased levels of self-efficacy, and negative-moderate associations between increased disability levels and fear of movement in patients with non-specific chronic low-back pain. These findings suggest that the three domains (physical, cognitive–evaluative, and motivational–emotional) can directly influence the ability to create movement representations. For patients with chronic pain, the information regarding the physical domain (the quality of afferent sensorimotor information, physical activity levels, and physical condition) appear to influence the direct modulation domain, thereby affecting the patient's ability to perform certain movements.

With regard to the integration of visual information and the formation of motor memory, Mattar and Gribble 2005 [70] stated that the learning of complex motor behavior is based on the acquisition of neural representations of mechanical requirements and movement parameters (coordination, strength, speed, etc.). The authors showed that acquiring neuronal representations of the properties of motor gestures through observation was a process independent from the use of conscious strategies. This conclusion was based on the implicit properties of the sensorimotor system. The authors also found that people undergoing AO training benefited from its effects even when attentional systems were engaged in a distracting task, such as arithmetic. The authors suggested that attention systems might be involved and could influence the process, but do not appear to be critical to the observation-mediated learning process. It is possible that the mathematical distraction task demanded a specific type of cognitive task, but left free other types of cognition mechanisms sufficient for creating motor strategies [70].

However, it has been reported that both explicit and implicit motor learning processes can occur [71]. For example, declarative knowledge can be used to create a set of rules leading to motor learning, with the ability to obtain information on the acquisition of a set of motor gestures without being aware of the processes that govern their acquisition [72]. This acquisition, with the participation of implicit or procedural memory, can occur simultaneously with practice (a process known as "online") or without it [73]. Explicit learning is particularly involved during the cognitive phase of motor learning when cognitive demand is high (i.e., explicit learning imposes major demands on working memory [74]). Implicit learning, however, occurs in the absence of the cognitive phase, and thus does not depend on the working memory [72].

The working memory is a complex process of active storage where information is susceptible to intra-individual manipulation. The information is consciously retained in the working memory for subsequent processing to guide behaviors [75]. One of the brain structures related to the working memory in the learning of implicit motor sequences is the dorsolateral prefrontal cortex [76]. Pascual-Leone et al. 1996 [77] found that interrupting the functioning of the contralateral dorsolateral prefrontal cortex notably affects and worsens the learning of a motor sequence.

The working memory consists of four key components [78]: the central executive, the phonological loop, the episodic buffer, and the visuospatial sketchpad. The central executive regulates the attentional process and is responsible for cognitive aspects involved in the process of information discrimination, facilitation, and inhibition. The phonological loop controls aspects related to the understanding and storage of verbal information. The episodic buffer is a storage and processing system that retrieves information from consolidated long-term memory, phonological loop, visuospatial sketchpad, and perception. The visuospatial sketchpad is related to the manipulation and reorganization of images and is relevant for planning motor gestures and retaining information on actions and objects in spatial memory [78].

Pascual-Leone et al. 1996 [77] showed the importance of the prefrontal cortex in acquiring motor gestures, and thus its role in the working memory, the latter of which requires activation of temporal and occipital regions. Visual information, therefore, appears to play an important role in the functioning of working memory and, consequently, in motor learning [78,79].

One of the most important brain structures related to the motor learning process is the cerebellum, which defines the automatic sequences associated with specific gestures [80,81]. A series of automatisms is performed through cerebellar activity, resulting in the execution of a given action. These automatisms work in conjunction with areas related to voluntary movement planning (premotor area and supplementary motor area) to select the correct motor plan [81,82]. Cerebellar functions and neurophysiological communication with secondary motor areas thus appear to be essential to the motor learning process. Lacourse et al. 2004 [83] found that movement representation increased cerebellar activity during the performance of various manual tasks, along with activity in other structures, thereby confirming the cerebellum's influence in the automation of voluntary movement.

Several studies have found that AO training led to greater motor learning of complex gestures in the short term than did MI [29,56]. Gatti et al. 2013 [56] argued that the human mirror neuron system, which consists of ventral premotor and lower parietal areas [84], works more efficiently, accurately, and adequately through AO. This improved functioning is because of the fact that the ventral premotor cortex (a region of the mirror neuron system largely related to the planning of voluntary movement) receives information from the visual cortex. AO training can, therefore, lead to greater functional neurophysiological activation than that provoked by MI, resulting in a greater influence on learning than MI.

At the neurophysiological level, Loporto et al. 2011 [85] found that AO can modulate the excitability of the corticospinal system (especially premotor cortex activity) by increasing the amplitude of motor evoked potentials. The authors argued that this finding could contribute to the learning of new motor gestures.

Lacourse et al. 2005 [60] found similar congruence in sensorimotor network activation in motor image generation through MI (both unpracticed and practiced motor tasks) when compared with the physical execution of the tasks. However, Vogt et al. 2007 [84] found that, during untrained AO, there was greater activation of the premotor cortex and lower parietal cortex than when the practiced actions were observed.

Another variable that could explain the greater impact of AO on motor learning than MI is perceived fatigue. Roure et al. 1999 [86] and Guillot et al. 2004 [87] reported that movement representation through MI can cause fatigue and difficulty maintaining attention. This loss of attention might be greater in MI-based practice than in AO training. Finally, Buccino, 2014 [4] argued that MI has been shown to have intrinsic limits that AO does not exhibit. MI appears to be a more complicated tool—in terms of cognitive demand, ability, effort, and concentration—than AO.

5. Conclusions

Several studies seem to support a number of the arguments presented in this hypothesis. Rizzolatti et al. 1996, 2004 [88,89] reported that the mirror neuron system, which offers the neuroanatomical support for these movement representation techniques, is widely involved in the motor learning process through movement representation

Given that mental practice lacks the physical execution of motor actions, both the quality and quantity of neurophysiological activity in the brain regions related to generating voluntary movement are important. There also appears to be a number of variables that can modulate this activity, especially in generating motor images through MI. The motivational–emotional domain would likely influence the entire system and, together with the physical and cognitive–evaluator domains, would influence motor learning.

In the direct comparison between AO and MI, AO training appears to be more efficient for creating mnemonic representations of movements as a prerequisite to learning. AO is also less demanding in terms of cognitive load, making it more robust and less susceptible to the influence of variables related to brain representation.

Despite its disadvantages, however, MI has a relevant role. Participants can create changing scenes and diverse situations through MI. However, participants' ability to generate motor images should be evaluated before performing MI-based interventions. The participants' physical condition and cognitive and emotional characteristics should be considered before implementing interventions that employ movement representation techniques. Finally, both sensorimotor neurotraining tools should be considered for the acquisition of new motor gestures, in combination, combined with physical practice and in isolation, depending on the context.

Author Contributions: Conceptualization, F.C.-M., L.S.-M., J.V.L.-H., and R.L.T.; methodology, F.C.-M. and R.L.T.; writing—original draft preparation, F.C.-M., L.S.-M., J.V.L.-H., and R.L.T.; writing—review and editing, F.C.-M., L.S.-M., J.V.L.-H., and R.L.T.; visualization, F.C.-M. and R.L.T.; supervision, F.C.-M. and R.L.T.; project administration, F.C.-M. and R.L.T.

Funding: This research received no external funding.

Acknowledgments: We thank the La Salle University Center for Advanced Studies for making this study possible

Conflicts of Interest: The authors declare no conflict of interest.

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Motor Effects of Movement Representation Techniques and Cross-Education Training in Recovery and Immobilisation Processes: A Systematic Review and Meta-Analysis

Brain training on motor outcomes in recovery and movement restriction processes

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Word count: 5645

Acknowledgements

The authors would like to thank Centro Superior de Estudios Universitarios CSEU La Salle for its services in editing this manuscript.

ABSTRACT

Objective: The main aim of this systematic review and meta-analysis was to assess the impact of movement representation techniques (motor imagery [MI], action observation [AO] and visual mirror feedback [VMF]) and cross-education (CE) training on strength, range of motion (ROM), speed, functional state and balance during experimental immobilisation processes in healthy individuals, in patients with injuries that did not require surgery and in those with surgical processes that did or did not require immobilisation.

Methods: MEDLINE, EMBASE, CINAHL and Google Scholar were searched. The last search was performed on 8 February 2020. A meta-analysis was conducted to determine the effectiveness of these techniques on motor variables in experimental immobilisation as well as during postsurgical or postinjury periods with or without immobilisation. Grading of Recommendations Assessment, Development and Evaluation was used to rate the quality, certainty and applicability of the evidence.

Results: Some 34 studies were included and 13 meta-analyses were conducted. Regarding the immobilised participants, in the healthy experimental individuals, MI showed significant results regarding maintenance of strength (standardised mean difference [SMD] 2.73; 95% CI 1.91–3.55; Q-value 0.06; p=0.8) and ROM (SMD 0.7; 95% CI 0.05–1.35; Q-value 0.0; p=0.99), with low-quality evidence.

Regarding the process with no immobilisation, 2 meta-analyses showed that VMF (SMD 2.33; 95% CI 0.33–4.34; Q-value 6.76; p=0.01; I^2=85%) and MI (SMD 1.21; 95% CI 0.11–2.3; Q-value 6.47; p=0.04; I^2=69%) techniques showed statistically significant changes in maintaining ROM in patients with injury without surgery, with very low-quality evidence. In addition, results had shown that MI demonstrated significantly higher maintenance of strength (SMD 1.26; 95% CI 0.71–1.8; Q-value 2.07; p=0.36; I^2=3%) and speed (SMD 0.56; 95% CI 0.08–1.03; Q-value 0.37; p=0.83; I^2=0%) in patients undergoing surgery, with low-quality evidence. No significant results were found with respect to ROM (SMD 0.7; 95% CI −0.89 to 2.29; Q-value 3.42; p=0.06; I^2=71%). Low-quality evidence showed that AO plus usual care could obtain significantly higher results with respect to maintenance of functional state (SMD 0.74; 95% CI 0.34–1.14; Q-value 3.54; p=0.32; I^2=15%) and balance (SMD 0.61; 95% CI 0.18–1.03; Q-value 3.92; p=0.17; I^2=24%) compared with usual treatment in isolation. CE training demonstrated maintenance of strength in patients undergoing surgery (SMD 0.65; 95% CI 0.33–0.96; Q-value 3.21; p=0.52; I^2=0%), with moderate evidence; however, not in healthy experimentally immobilised individuals (SMD 1.85; 95% CI −0.07 to 3.77; Q-value 14.82; p<0.01; I^2=87%). Finally, VMF did not show significant results in maintaining ROM after surgery without immobilisation (SMD 0.46; 95% CI −0.06 to −0.98; Q-value 7; p=0.07; I^2=57%), nor did MI in

maintaining strength after surgery and immobilisation (SMD 0.13; 95% CI −0.37 to −0.64; Q-value 0.9; p=0.34).

Conclusions: Movement representation techniques and CE training have been shown to have a significant impact on the improvement of various motor variables in particular and on physical maintenance in general during experimental immobilisation processes in healthy individuals, in patients with injuries that did not require surgery and in surgical processes that did or did not require immobilisation; however, further research is still needed due to several discrepancies.

Keywords: Movement representation techniques, Cross education, Limb immobilisation, Motor imagery, Action observation, Visual mirror feedback, Mirror therapy, Motor variables, Range of motion, Strength, Functional state, Balance, Walking speed.

Key points

-Movement representation techniques and cross-education are a set of very low-cost techniques shown to have a significant impact on the improvement of motor function during the recovery and immobilisation processes.

-Action observation and cross-education seem to benefit injured patients undergoing surgery whereas motor imagery and visual mirror feedback appear to work better in healthy individuals undergoing experimental immobilisation and in injuries not requiring surgery.

1. INTRODUCTION

After an orthopaedic injury or a surgical procedure, immobilisation or movement restriction of the injured limb, either due to pain, injury or the use of external immobilisation, is a common scenario. Movement reduction or limb disuse can lead to neuroplastic, neurobiological and sensorimotor changes, both in neuromuscular function and at the supramedullary level [1,2].

Recently, research has found that loss of muscle size and strength occurs along with the presence of changes in neuromuscular function at the peripheral level and at the central level, with changes in muscle fibre excitability and contractility, as well as a reduction in spinal and corticospinal excitability and reduced central movement drive to the muscle [1]. In addition, limb immobilisation for at least 2 weeks has been found to be associated with a process of cortical reorganisation in the thickness of the motor area primarily responsible for the specific body region, as well as its associated somatosensory cortex. A reduction in thickness was found in both brain regions. At the white matter level, a decrease in the corticospinal tract volume was also found. It therefore appears that cortical depression occurs during immobilisation of a limb [2].

These changes produced by the immobilisation or disuse of a limb can lead to a reduction in functional variables of muscle strength, range of motion (ROM) or coordination, which has been associated with increased complications and recovery times [3,4]. Therefore, in recent years, research has been focused on developing new treatment alternatives that can reduce the potential impact of immobilisation or disuse after a musculoskeletal injury and improve recovery processes. Some of these alternatives, such movement representation techniques or cross-education (CE) training, attempt to promote central nervous system activity to avoid cortical depression processes and thus prevent functional alterations. The main common factor in these techniques is that it is possible to influence the affected limb without the need for its active movement, leading to a great many possibilities for intervention when active movement is not possible.

These techniques have in common that they lead to an activation of the areas related to the planning, adjustment and automation of voluntary movement in a similar manner as to when the action occurs in a real manner. These techniques are motor imagery (MI), action observation (AO), mirror therapy and visual mirror feedback (VMF). MI is defined as a dynamic mental process that involves the representation of an action, in an internal manner, without its real motor output [5]. AO, however, evokes an internal, real-time simulation of what the observer is seeing [6]. VMF is defined as the reflective illusory movement perception in one limb upon viewing the moving opposite limb in a midsagittal mirror [7]. On the other hand, CE, first described in the 19th century by Scriture et al. [8], is defined as an increased capacity to generate strength with the untrained limb as a result of training the other limb unilaterally [9]. In this regard, previous research has suggested that a CE strength task could have led to cortical excitability and a motor learning effect that was reflected in improvements in performance in the untrained left arm [9,10].

It was therefore the main aim of this systematic review and meta-analysis to assess the impact of movement representation techniques and CE training on strength, ROM, speed, functional state and balance during experimental immobilisation processes in healthy individuals, in patients with injuries that did not require surgery and in surgical processes that did or did not require immobilisation.

2. METHODS

This systematic review and meta-analysis was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analysis guidelines described by Moher et al. [11]. The protocol of this systematic review and meta-analysis was registered (7 February 2020) in an international register prior to starting the review (PROSPERO). Once registered, however, due to a delay in the system, this study was performed before the registration number could be received.

2.1 Inclusion criteria

The selection criteria used in this systematic review and meta-analysis were based on methodological and clinical factors, such as the Population, Intervention, Control, Outcomes, and Study design described by Stone [12].

2.1.1 Population

The participants selected for the studies were older than 18 years, and were asymptomatic individuals or patients who met at least one of the following conditions: (a) experimental immobilisation; (b) patients with fracture or injury, with or without immobilisation; or (c) postsurgical patients with or without immobilisation. The participant's sex was irrelevant.

2.1.2 Intervention and control

The interventions were movement representation techniques (MI, AO or VMF) and CE strategy. The intervention could be given as an independent intervention, added to an intervention or embedded in an intervention (e.g., usual care or conventional treatment). Regarding MI, both visual and kinaesthetic strategies as well as both perspectives of movement representations could be considered (first or third). Studies that used a combination of various movement representation techniques (e.g., graded motor imagery [GMI], consisting of implicit MI, explicit MI and VMF) were also included. Regarding the control group, the comparators were conventional intervention or usual care (physical therapy, exercise intervention) in combination or not with placebo interventions (cognitive task, relaxation).

2.1.3 Outcomes

The measures used to assess the results and effects were the following motor variables: ROM, balance, strength, functional state and walking speed.

2.1.4 Study design

Randomised controlled trials (RCTs), randomised parallel-design controlled trials (RPCTs) and prospective controlled clinical trials were selected.

2.2 Search strategy

The search for studies was performed using MEDLINE (PubMed), EMBASE, CINAHL and Google Scholar. The final search was run on 8 February 2020.

A validated search filter was used and adapted to all the databases [13–15]. Based on international criteria, no restriction was applied with respect to the language of the studies [16]. Using the same methodology, 2 researchers conducted the search for the studies independently. Consensus served to resolve possible differences between them. In addition, manual searching through journals that usually publish on the topic in question was used to include all available articles. In all the articles found in a first search, the 'Introduction', 'Discussion' and 'Reference' sections were reviewed in order not to miss any relevant articles. Mendeley's appointment management software (Mendeley desktop v1.17.4, Elsevier, New York, NY, USA) was used to remove duplicate articles [17].

2.3 Selection criteria and data extraction

First, a data analysis was performed by 2 independent reviewers (F.C.M and L.S.M), who assessed the relevance of the RCTs regarding the study questions and aims. This first analysis was made based on information from the Title, Abstract and Keywords of each study. If there was no consensus or the abstracts did not contain enough information, the full text was reviewed.

Second, the full text was used with the aim of assessing whether the studies met all the inclusion criteria. Differences between both independent reviewers were resolved by a process of consensus moderated by a third reviewer (R.L.T) [18]. Data described in the results were extracted by means of a structured protocol that ensured that the most relevant information was obtained from each study [19].

2.4 Methodological quality assessment

The Cochrane Handbook for Systematic Reviews of Interventions version 5.1.0 was used to assess the risk of bias [19]. This assessment tool covers a total of 7 domains: (1) random sequence generation (selection bias); (2) allocation concealment (selection bias); (3) blinding of participants and personnel (performance bias); (4) blinding of outcome assessment (detection bias); (5) incomplete outcome data (attrition bias); (6) selective reporting (reporting bias); and (7) other biases. Bias risk was assessed as low, high or unclear.

Two independent reviewers (F.C.M and L.S.M) examined the quality of all the selected studies using the same methodology; disagreements between reviewers were resolved by consensus including a third reviewer (R.L.T). The concordance between the results (inter-rater reliability) was performed using Cohen's kappa coefficient (κ): (1) $\kappa > 0.7$ means high level of agreement between assessors; (2) κ

= 0.5–0.7 is a moderate level of agreement; and (3) $\kappa < 0.5$ is a low level of agreement [20].

2.5 Qualitative analysis

The qualitative analysis was based on classifying the results into levels of evidence according to the Grading of Recommendations, Assessment, Development and Evaluation (GRADE), which is based on 5 domains: (1) study design; (2) imprecision; (3) indirectness; (4) inconsistency; and (5) publication bias [21].

Evidence was categorised into the following 4 levels accordingly: (a) *High quality*: Further research is very unlikely to change our confidence in the estimate of effect, and all 5 domains are met. (b) *Moderate quality*: Further research is likely to have an important impact on our confidence in the estimate of effect and might change the estimate of effect. One of the 5 domains is not met. (c) *Low quality*: Further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate. Two of the 5 domains are not met. (d) *Very low quality*: Any estimate of effect is very uncertain. Three of the 5 domains are not met [22,23].

The assessment of the 5 domains was conducted according to GRADE criteria. Regarding the study design domain: the recommendations were downgraded 1 level in case there was an uncertain or a high risk of bias and serious limitations in the estimate of the effect. Regarding inconsistency, recommendations were downgraded 1 level when point estimates varied widely among studies, when confidence intervals (CIs) showed minimal overlap or when the I^2 was substantial or large. In terms of the indirectness domain, recommendations were downgraded when significant differences in interventions, study populations or outcomes were found. In relation to imprecision, domain recommendations were downgraded 1 level if there were n<400 participants for continuous data. Finally, recommendations were downgraded due to the strong suspicion of publication bias by funnel plot and Egger's regression test analysis.

2.6 Data synthesis and analysis

The statistical analysis was conducted using meta-analysis with interactive explanation software (MIX, version 1.7) [24]. To provide a comparison between outcomes reported by the studies, the standardised mean difference (SMD) over time and corresponding 95% CI were calculated for the continuous variables. The statistical significance of the pooled SMD was examined as Hedges' g, to account for possible overestimation of the true population effect size in small studies [25].

The same 3 inclusion criteria were used for the systematic review and for the meta-analysis: (1) the results showed detailed information regarding the comparative statistical data of the exposure factors, therapeutic interventions and treatment responses; (2) the intervention was compared with a similar control group (e. g., usual care or conventional physical therapy protocol); and (3) data on the analysed variables were represented in at least 2 studies.

The estimated SMDs were interpreted as described by Hopkins et al. [26]; i.e., an SMD of 4.0 was considered to represent an extremely large clinical effect, 2.0–4.0 a very large effect, 1.2–2.0 a large effect, 0.6–1.2 a moderate effect, 0.2–0.6 a small effect and 0.0–0.2 a trivial effect. The degree of heterogeneity among the studies was estimated by the Cochran's Q statistical test (a p value <0.05 was considered significant) and the inconsistency index (I^2) [27]. I^2>25% was considered to represent small, I^2>50% medium and I^2>75% large heterogeneity [28]. The I^2 index is a complement to the Q test, although it has the same problems of power with a small number of studies [28]. When the Q-test was significant (p<.1) and/or the result of I^2 is >75%, this indicated that there was heterogeneity among the studies and the random-effects model was conducted in the meta-analysis. To detect publication biases and test the influence of each individual study, a visual evaluation of the funnel plot and exclusion sensitivity plot, seeking asymmetry, was performed. We also employed Egger's regression tests to assess publication bias [29].

3. RESULTS

The study search strategy is shown in the form of a flow chart **(Fig. 1)**. A total of 34 articles that met the inclusion criteria were selected. Of the total number of articles included, 12 had performed complete immobilisation due to surgery or an experimental condition. The remaining 22 articles included participants who had surgery or an orthopaedic injury to the musculoskeletal system that restricted movement, although they did not receive external mobilisation. The characteristics for which data were extracted (sample size, demographic characteristics, intervention, outcomes, main results and conclusions) are presented in **Table 1** (immobilisation) and **Table 2** (no immobilisation).

3.1 Methodological quality analysis

The quality of all the studies was evaluated with the Cochrane assessment tool. Most of the studies had a low risk of selective reporting bias. The domain with the highest percentage of studies with a high risk of bias was the blinding of participants and personnel (performance bias). The risk of bias summary and risk of bias graph are shown in **Fig. 2** and **Fig. 3**, respectively. The inter-rater reliability of the methodological quality assessment between assessors was high ($\kappa=0.813$).

3.2 Study population characteristics

The total number of participants was 976. The number of participants included with immobilisation was 313, and without immobilisation 663.

Regarding immobilisation studies, the nature of the immobilisation was experimental in 9 studies [30–38] and due injury [39] or surgery [40,41] in 3 studies. In relation to the no immobilisation studies, 5 were nonsurgical procedures and included patients with orthopaedic injuries: 2 ankle sprain [42,43], 1 shoulder impingement [44], 1 adhesive capsulitis [45] and 1 orthopaedic hand injury [46]. Seventeen studies were surgical procedures: 4 were anterior cruciate ligament reconstruction procedures [47–50], 7 were knee surgery or knee replacement [51–57], 3 were hip replacement [58–60] and 3 were orthopaedic hand injuries [61–63].

3.3 Interventions

Regarding the immobilisation studies, 6 used MI or GMI as an experimental intervention [30–32,34,40,41] and 6 used a CE intervention [33,35–39]. Regarding the no immobilisation studies, 8 employed MI [42,43,47,51–53,58], 5 used VMF [45,46,61–63], 4 used AO [54–56,59] and 3 used CE [48–50]. Frenkel et al. had combined VFM with MI [57] and Marusic et al. had combined MI and AO [60]. Regarding control comparisons, all studies included standard rehabilitations as a control group, except the studies that used an experimental immobilisation that used no intervention as a control group. In addition, Villafañe et al. and Cupal & Brewer [47,56] used a sham intervention.

3.4 Systematic review and meta-analysis results

3.4.1 Immobilisation

3.4.1.1 Experimental immobilisation

Motor imagery

Strength

The meta-analysis showed statistically significant differences for the MI intervention, with a very large clinical effect in 2 studies [31,34] (n=46; SMD 2.73; 95% CI 1.91–3.55; heterogeneity Q value 0.06; p=0.8) **(Fig. 4A)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1A).

Range of motion

The meta-analysis showed statistically significant differences for MI intervention with a moderate clinical effect in 2 studies [30,32] (n=39; SMD 0.7; 95% CI 0.05–1.35; heterogeneity Q value 0; p=0.99) **(Fig. 4B)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1B).

Cross-education

Strength

The meta-analysis did not show statistically significant differences in the CE intervention in 3 studies [33,37,38] (n=51; SMD 1.85; 95% CI −0.07 to 3.77; heterogeneity Q value 14.82; p<0.01; inconsistency I^2=87%), and there was no evidence of publication bias in the meta-analysis (Standard error [SE]=1.13; t=−3.04; p=0.2) **(Fig. 4C)**. The shape of the funnel plot appeared to be asymmetrical in the dominant model (Annex 1C). The sensitivity exclusion analysis suggested that 2 studies (Andrushko et al. and Pearce et al. [33,38]) significantly affected pooled SMD (Annex 1D). Egger's test results suggested no significant evidence of publication bias for the analysis (intercept=1.93; t=4.26; *p*=0.15).

3.4.1.2 Surgery immobilisation

Motor imagery

Strength

The meta-analysis did not show statistically significant differences in MI intervention in 2 studies [40,41] (n=61; SMD 0.13; 95% CI −0.37 to 0.64; heterogeneity Q value 0.9; *p*=0.34) **(Fig. 4D)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1E).

3.4.2 No immobilisation

3.4.2.1 Surgery

Action observation

Balance

The meta-analysis showed statistically significant differences in AO interventions with a moderate clinical effect in 4 studies [54–56,59] (n=132; SMD 0.61; 95% CI 0.18–1.03; heterogeneity Q value 3.92; p=0.17; inconsistency I^2=24%), and there was no evidence of publication bias in the meta-analysis (SE=1.07; t=0.58; p=0.62) **(Fig. 5A)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1F). The sensitivity exclusion analysis suggested that 1 study (Belleli et al. [55]) significantly affected pooled SMD (Annex 1G). Egger's test results suggested no significant evidence of publication bias for the analysis (intercept=−2.98; t=−0.03; p=0.98).

Functional state

The meta-analysis showed statistically significant differences in AO interventions with a moderate clinical effect in 4 studies [54–56,59] (n=132; SMD 0.74; 95% CI 0.34–1.14; heterogeneity Q value 3.54; p=0.32; inconsistency I^2=15%), and there was no evidence of publication bias in the meta-analysis (SE=0.52; t=−0.5; p=0.67) **(Fig. 5B)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1H). The sensitivity exclusion analysis suggested that no study significantly affected the pooled SMD. Egger's test results suggested no significant evidence of publication bias for the analysis (intercept=1.43; t=1.94; p=0.19).

Visual mirror feedback

Range of motion

The meta-analysis did not show statistically significant differences in the VMF intervention in 4 studies [57,61–63] (n=141; SMD 0.46; 95% CI −0.06 to 0.98; heterogeneity Q value 7; p=0.07; inconsistency I^2=57%), and there was no evidence of publication bias in the meta-analysis (SE=2.62; t=−0.28; p=0.81) **(Fig. 5C)**. The shape of the funnel plot appeared to be asymmetrical in the dominant model (Annex 1J). The sensitivity exclusion analysis suggested that 3 studies significantly affected pooled SMD (Frenkel et al. [57]; Albolfazli et al. [61]; Bayón-Calatayud et al. [62]) (Annex 1I). Egger's test results suggested no significant evidence of publication bias for the analysis of pain intensity (intercept=7.57; t=0.45; p=0.7).

Cross-education

Strength

The meta-analysis showed statistically significant differences in the CE intervention with a moderate clinical effect in 3 studies [48–50]. Two studies included different training dosage groups; thus, a total of 5 groups were included in the analysis (n=163; SMD 0.65; 95% CI 0.33–0.96; heterogeneity Q value 3.21; p=0.52; inconsistency I^2=0%), and there was no evidence of publication bias in the meta-analysis (SE=0.73; t=−2.77; p=0.07) **(Fig. 5D)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1K). The sensitivity exclusion analysis suggested that no study significantly affected the pooled SMD. Egger's test results suggested no significant evidence of publication bias for the analysis (intercept=2.02; t=3.67; *p*=0.03).

Motor imagery

Strength

The meta-analysis showed statistically significant differences in MI interventions with a large clinical effect in 3 studies [47,52,53] (n=66; SMD 1.26; 95% CI 0.71–1.8; heterogeneity Q value 2.07; *p*=0.36; inconsistency I^2=3%), and there was no evidence of publication bias in the meta-analysis (SE=0.63; t=−3.34; *p*=0.19) **(Fig. 6A)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1L).The sensitivity exclusion analysis suggested that no study significantly affected pooled SMD. Egger's test results suggested no significant evidence of publication bias for the analysis (intercept=1.32; t=5.37; *p*=0.12).

Walking speed

The meta-analysis showed statistically significant differences in MI interventions with a moderate clinical effect in 3 studies [58,60,64] (n=71; SMD 0.56; 95% CI 0.08–1.03; heterogeneity Q value 0.37; *p*=0.83; inconsistency I^2=0%), and there was no evidence of publication bias in the meta-analysis (SE=1.73; t=−1.01; *p*=0.5) **(Fig. 6B)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1M). The sensitivity exclusion analysis suggested that 2 studies significantly affected the pooled SMD (Marusic et al. [60] and Paravlic et al. [64]) (Annex 1N). Egger's test results suggested no significant evidence of publication bias for the analysis (intercept=4.11; t=1.33; p=0.41).

Range of Motion

The meta-analysis did not show statistically significant differences in MI intervention in 2 studies [51,52] (n=30; SMD 0.7; 95% CI −0.89 to 2.29; heterogeneity Q value 3.42; p=0.06; inconsistency I^2=71%) **(Fig. 6C)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1O).

3.4.2.2 Injury

Visual mirror feedback

Range of motion

The meta-analysis showed statistically significant differences in VMF interventions with a large clinical effect in 2 studies [45,46] (n=163; SMD 2.33; 95% CI 0.33–4.34; heterogeneity Q value 6.76; p=0.01; inconsistency I^2=85%) **(Fig. 7A)**. The shape of the funnel plot appeared to be asymmetrical in the dominant model (Annex 1P).

Motor imagery

Range of motion

The meta-analysis showed statistically significant differences in MI interventions with a large clinical effect in 3 studies [42,44,65] (n=54; SMD 1.21; 95% CI 0.11–2.3; heterogeneity Q value 6.47; p=0.04; inconsistency I^2=69%), and there was no evidence of publication bias in the meta-analysis (SE=−3.98; t=−4.42; p=0.14) **(Fig. 7B)**. The shape of the funnel plot appeared to be symmetrical in the dominant model (Annex 1Q). The sensitivity exclusion analysis suggested that 2 studies (Christakou et al. [65] and Hoyek et al. [44]) significantly affected the pooled SMD (Annex 1R). Egger's test results suggested no significant evidence of publication bias for the analysis (intercept=1.66; t=5.69; p=0.11).

3.5 Qualitative analysis

With respect to experimental immobilisation, and according to the GRADE recommendations, there was low-quality evidence regarding the effects of MI on strength and ROM, downgraded due to imprecision and a risk of bias.

In relation to the no immobilisation studies and postsurgery patients, there was low-quality evidence regarding the effects of AO on balance and functional status, downgraded due to imprecision and a risk of bias. In addition, there was low-quality evidence in relation to MI interventions for strength and walking speed, downgraded due to imprecision and a risk of bias. On the other hand, there was moderate evidence regarding CE training and strength improvements, also downgraded due to imprecision.

Finally, regarding the no immobilisation studies and injury patients, there was very low-quality evidence in VFM and MI interventions for ROM outcome, downgraded due to imprecision, a risk of bias and inconsistency.

4. DISCUSSION

The present systematic review and meta-analysis showed some relevant results regarding the behaviour of some motor variables after the implementation of various movement representation techniques and CE training in various clinical scenarios or experimentally generated nonclinical settings.

Through the assessment of the change in motor function, some key aspects can be indirectly evaluated, such as the processes of motor relearning after injury or immobilisation; i.e., after maintained disuse. The recovery process can be assessed of the physiological values of some important neurosensorimotor system variables, such as strength, speed, balance and functional state, by preventing or minimising a process of disuse due to injury, surgery or immobilisation situations.

The results of this systematic review and meta-analysis can be divided into 2 main groups: studies of people undergoing a process of immobilisation and studies in which a process of immobilisation was not implemented.

With respect to the immobilised participants, a total of 4 meta-analyses were included: 3 with healthy individuals immobilised experimentally and 1 with patients submitted to a surgical process. The results in this first group showed that in the healthy experimentally immobilised individuals, MI showed significant results with respect to maintenance of strength and ROM, with low-quality evidence. These results did not occur with the application of CE training. In patients undergoing surgery, MI did not show significant changes in strength maintenance.

Regarding to the group of studies that dealt with participants not undergoing an immobilisation process, 9 meta-analyses were included, which can also can be divided into 2 groups: studies of patients with injury who did not require surgery and of patients with an injury who required surgery. First, the quantitative analysis of 2 meta-analyses showed that the application of VMF or MI techniques, in combination with usual care, showed statistically significant changes in maintaining ROM in patients with injury without surgery, with very low-quality evidence. Second, the quantitative analysis of 7 meta-analyses showed that the MI technique, in combination with usual care, showed significantly higher maintenance of strength and speed in patients undergoing surgery, with low-quality evidence. However, this outcome was not found with respect to the ROM variable. In addition, low-quality evidence showed that AO plus usual care obtained significantly better results with respect to maintenance of functional state and balance compared with usual treatment in isolation, and the use of the VMF technique did not maintain ROM better than not applying the technique in surgical patients. Finally, the application of CE training showed a maintenance of strength in patients undergoing surgery, with moderate evidence.

Thus, regarding techniques, AO showed good results with respect to improvements in general functional state and with respect to improvements in balance in patients with injury undergoing surgery. CE training appears to have worked better in patients compared with healthy individuals who were immobilized experimentally. VMF appears to have worked better in injuries that did not require surgery compared with those that did. However, MI showed some results that should be further analysed. With respect to ROM maintenance, it appears that MI worked better when immobilisation was experimental or in patients who had injury but did not require surgery. However, in patients with injuries undergoing surgery, MI did not show significant results regarding ROM maintenance. With respect to strength, MI showed similar results; i.e. better results in healthy individuals with experimental immobilisation and in patients with injury not requiring surgery, and poorer in patients undergoing surgery. Finally, MI showed good results with respect to maintenance of speed.

The maintenance of physical condition, and therefore the specific state of some motor variables after an experimental immobilisation process or after a clinical process with or without surgery (e.g., regaining strength, motor relearning through the recovery of active ROM, maintenance of balance or speed), could indirectly reveal the state of brain region function in relation to the planning, automation and execution of voluntary movement, as well as those areas involved in the generation of strength (e.g., primary motor cortex, premotor cortex, supplementary motor area, base ganglia, cerebellum) [66,67].

For example, Ranganathan et al. [66] had shown that force recovery originates through an adaptive neuroplastic process in the activity performance of cortical regions leading to the motor units generating both higher intensity and the recruitment of a set of motor units that would normally remain without activity.

In relation to this, Moukarzel et al. [52] has recently found that MI could be relevant to promoting motor relearning as well as motor recovery in patients with knee impairments. These authors, as well as other research groups [68,69], have argued that the combination of muscle atrophy along with a deficit of neuromuscular activation are contributing factors to the reduction in muscle strength. Through MI, an adaptive neuroplastic process of cortical reorganisation is likely to take place, thus improving movement readiness and resulting in increased motor recruitment and synchronisation of motor units at the peripheral level [52]. This result is what could explain and lead to an improvement in motor variables such as strength or active ROM.

Although quantitatively lower, due to the fact that movement representation techniques (AO, VMF and MI) have the ability to qualitatively activate the same areas at a cortical level as those activated during voluntary movement [7,70,71], it is likely that this explanation could be applied to any of the 3 techniques.

Therefore, as postulated by Moukazel et al. [52], it appears that movement representation techniques could increase, enhance and improve the readiness of voluntary movement through a process of reorganisation at the cortical level, indirectly causing greater voluntary muscle activation and greater active ROM. Grangeon et al. [72] also argued that improved accuracy of neurosensory motor control in a neurological patient undergoing surgery for tendon transfer with real practice plus mental practice should be associated with structural neuroplastic changes at the cortical level. This association was also claimed by Jackson et al. [73]. In this regard, it has been shown that mental unilateral movement provokes bilateral brain activity in similar brain regions as does physical movement [74].

In fact, a large number of theories or explanations that aim to explain the effect of movement representation techniques on peripheral muscle activity have been proposed. The study conducted by Christakou et al. [65] shows some of these explanations in an exceptional way. For example, they describe Carpenter's ideomotor hypothesis from the end of the 19th century [75] and Jacobson's psychoneuromuscular theory in the 1930s [76]. The latter proposes that the construction of gestural motor images could evoke neuromuscular responses in the muscles involved. This evocation was later proven by Hale and his research group [77]. There is also the neural training hypothesis proposed by authors Sale and Enoka & Fuglevand, which suggests that changes at a central level are those that cause an increase at a peripheral level of muscular activity [65,78]. Along these lines, Jowdy and Harris [74] found a significant increase in muscle activity during movement representation tasks evaluated through surface electromyography. Finally, it has been found that the construction of movement images could lead to a better representation of the process of motor force generation at the central level, i.e., in the central programming and planning system of the cerebral cortex. [67,79]. All this could explain why training through movement representation techniques might have an impact at a central level and consequently at a peripheral level.

Regarding ROM, attentional control theory suggests that participants who perform a mental movement process might be able to focus their attention on the appropriate muscles more easily, which could improve the learning of motor skills. It has also been proposed that other neurophysiological aspects, such as the modulation of corticospinal excitability or the involvement of the autonomic nervous system, could be related to motor changes following mental movement representation [80].

Our results are consistent with other review studies. Yap & Lim [81] found in their meta-analysis that MI was effective for the improvement in ROM among patients with chronic musculoskeletal pain. The systematic review and meta-analysis recently conducted by Peng et al. [82] showed that AO improved a set of motor variables, including motor function, walking ability and gait velocity in neurologic patients. However, controversial results have also been found. For example, the recent meta-analysis conducted by Manochi et al. [83] did not find evidence that movement representation techniques are effective in increasing strength in healthy individuals. We found different results. In addition, Paravlic et al. [64] found that MI caused an increase in maximum voluntary force significantly greater than no intervention in healthy adults.

In regard to CE training, Lee & Carroll conducted a thorough review of the neural, spinal and peripheral adaptations that occur during this training [9]. They proposed 2 nonexclusive hypotheses to explain its effects: modification of contralateral motor pathways and the relationship between CE and motor learning. This second hypothesis shares similarities with respect to the arguments above regarding the possible functioning of movement representation techniques. In this second hypothesis, the authors argue that the generation of neural adaptations that occur during CE is likely to be in areas related to the control and execution of the trained member's voluntary movement. However, these modified neural circuits could be accessed during the untrained limb's voluntary contractions, optimising the descending command signals from the untrained hemisphere. This hypothesis appears to have been supported by Strens et al. [85]. In addition, the meta-analysis study conducted by Manca et al. (a). [86] found that sustained CE training caused a reduction in inhibitory mechanisms at the cortical level, suggesting that inhibitory phenomena occurring within the primary motor cortex could modulate corticospinal inhibition and excitability after contralateral training.

Regarding the comparison of results with other review studies, we found some data that could generate controversy with the current state of the art. For example, the meta-analysis conducted by Manca et al. (b). [87] showed that CE training caused significant changes in strength. These changes did not occur in the present meta-analysis because the study by Pawar et al. appears to have reduced the result to a nonsignificant value (see Figure 5D). One of the main differences between our study and that of Manca et al (b). is that they excluded studies that dealt with individuals with an immobilisation.

Limitations

This study has some limitations. Although a systematic search strategy was followed, the risk of selection bias might still be present. Another limitation is the number of studies included in the meta-analysis, given this low number could represent inadequate statistical power and bias due to the sample size included in each comparison. In this regard, the low number of studies included could represent a bias in the interpretation of asymmetry in each forest plot; therefore, this situation should be interpreted with caution. Most of the studies did not include a placebo intervention in addition to usual treatment, which makes it difficult to determine whether effects were driven by movement representation techniques and not due to nonspecific effects. Finally, a major limitation was including all studies, including those with very low methodological quality.

5. CONCLUSIONS

Movement representation techniques and CE training are a set of very low-cost techniques shown to have a significant impact on the improvement of various motor variables in particular, and on physical maintenance in general, during experimental immobilisation processes in healthy individuals, in patients with injuries that did not require surgery and in surgical processes that did or did not require immobilisation.

AO and CE training appear to benefit injured patients undergoing surgery, whereas MI and VMF appear to work better in healthy individuals undergoing experimental immobilisation and in injuries not requiring surgery. However, the results of these techniques in maintaining physical condition were not significant in injuries requiring surgery. This study shows that movement representation techniques and CE training are valuable tools for physical maintenance, but further research is still needed due to several discrepancies.

Compliance with Ethical Standards

Declarations

No conflicts of interest

Funding

No sources of funding were used to assist in the preparation of this article

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Table 1. Characteristics of the included studies on immobilization.

Trial	Nature of the immobilization	Body area	Participants	Intervention	Control	Outcome measures	Results and conclusions
Frenkel et al., 2014	Experimental (for 3 weeks)	Nondominant forearm	Young healthy men (n=18; 20 to 30 y)	Mental practice group: contralateral physical training plus MI, guided and unsupervised training (n=9)	No training (n=9)	ROM (wrist joint) in flexion, extension, adduction and abduction	Mental practice may prevent a loss of hand function associated with mid-term limb immobilization
Newsom et al., 2003	Experimental (for 10 days)	Nondominant forearm	Young healthy subjects (n=17, 13 women and 4 men; 18 to 30 y)	Mental practice group: MI, 3 sessions daily (n=9, 5 women and 4 men)	No training (n=8 women)	ROM (wrist joint) in flexion and extension, and hand grip strength	MI may be useful in preventing the strength loss associated with short-term immobilization
Einsiedel et al., 2011	Experimental (for 3 weeks)	Nondominant forearm	Right-handed healthy men (n=21)	Mental practice group: MI, 3 $d \cdot wk^{-1}$ (n=11)	No training (n=10)	ROM (wrist joint) in flexion, extension, adduction and abduction	The application of MI had significantly greater effects than the control group on the preservation of the initial functional state after immobilization

Clark et al., 2014	Experimental (for 4 weeks)	Nondominant wrist-hand immobilization	Young healthy subjects (n=44)	Mental practice group: MI, 5 d·wk^{-1} (n=14, 20.9±3.6)	-No training (n=15, 21.2±3.5 y) -No training and no immobilization (n=15, 21.5±3.4 y)	Isometric muscle strength	MI attenuates disuse-induced losses in strength
Andrushko et al., 2018	Experimental (for 4 weeks)	Nondominant forearm	Young healthy subjects (n=16, 13 women and 3 men)	CE: resistance training- eccentric wrist, 3 d·wk^{-1} (n=8, 7 women and 1 man)	No training (n=8, 6 women and 2 men)	Wrist flexors and extensors eccentric, concentric and isometric MVC, muscle thickness, and forearm muscle C-SA	CE preserved size of the immobilized contralateral muscle and strength across multiple contraction types
Farthing et al., 2009	Experimental (for 3 weeks)	Nondominant forearm	Right-handed healthy subjects (n=30, 22 women and 8 men)	CE: maximal isometric ulnar deviation, 5 d·wk^{-1} (n=10, 20.9±2.4 y)	-No training (n=10, 22.2±2.8 y) -No training and no immobilization (n=10, 25.4±3.0 y)	Peak torque, EMG, and muscle thickness	CE attenuated strength loss in the immobilized limb during unilateral immobilization
Farthing et al., 2011	Experimental (for 3 weeks)	Nondominant forearm	Right-handed healthy subjects (n=14, 12 women and 2 men)	CE: maximal isometric handgrip contractions, 5 d·wk^{-1} (n=7, 20.6±1.4 y)	No training (n=7, 22.7±4.4 y)	Peak force, EMG and muscle thickness	CE attenuated strength loss in the immobilized limb during unilateral immobilization

Magnus et al., 2010	Experimental (for 4 weeks)	Nondominant arm	Right-handed healthy subjects (n=25)	CE: maximal isometric elbow flexion and extension, 3 d·wk^{-1} (n=8, 20.9±3.2 y)	-No training (n=8, 20.3±1.8 y) -No training and no immobilization (n=9, 24.9±5.1 y)	Isometric strength, muscle thickness, MVA, and EMG	CE effects on the immobilized arm was greater after elbow extension training
Pearce et al., 2012	Experimental (for 3 weeks)	Nondominant arm	Right-handed healthy subjects (n=28, 15 women and 13 men)	CE: unilateral arm curl strength training, 3 d·wk^{-1} (n=9, 26.5±7.6 y, 5 women and 4 men)	-No training: nondominant arm rested in a sling during 15 h·day^{-1} (n=9, 25.3±8.7 y, 5 women and 4 men) -No training and no immobilization (n=10, 23.8±6.0 y, 5 women and 5 men)	1-RM strength. Isometric MVC and muscle thickness	CE training of the free limb successfully maintained strength and muscle thickness of the contralateral immobilized limb
Magnus et al., 2013	After injury (for 40.4±6.2 days, non-surgery)	Forearm	Women older than 50 with distal radius fracture (n=39)	SR (forearm casting + hand exercises) plus CE, 3 d·wk^{-1} during 26 wk (n=10, 20.6±1.4 y)	SR, 3 d·wk^{-1} (n=10, 22.7±4.4 y)	Peak force, ROM (flexion, extension, pronation and supination) and function.	CE training after a distal radius fracture was associated with improved strength and ROM in the fractured limb

Stenekes et al., 2009	After surgery (for 6 weeks)	Hand	Patients after flexor tendon repair (n=25)	MI of finger flexion movements during the postoperative dynamic splinting period, 8 sessions·day plus SR (n=12, 36.1±11.3)	SR (n=13, 31.1±10.0)	Central aspects of hand function (grip strength and active total ROM)	There were no significant differences between MI- and control-group in active total ROM and in grip strength
Dilek et al., 2017	After surgery (for 6 weeks)	Forearm	Patients after distal radius fracture (n=36)	Graded MI plus SR, 2 d·wk^{-1} during 8 wk (n=17, 52.59±9.8)	SR, 2 d·wk^{-1} during 8 wk (n=19, 47.16±10.5)	Forearm and hand active ROM (wrist flexion, extension, ulnar and radial deviation, and forearm supination and pronation) and grip strength	Graded MI showed beneficial effects to improve grip strength and increase upper extremity functions

MI: Motor imagery; ROM: Range of movement; CE: Cross-education; MVC: Maximal voluntary contractions; C-SA: Cross-sectional area; y: years; d·wk^{-1}: days per week; EMG: electromyography; h·day^{-1}: hours per day; 1-RM, 1 repetition maximum; PT: Physical therapy; SR: Standard rehabilitation.

Table 2. Characteristics of the included studies without immobilization

Trial	Medical procedure (surgical/non-surgical)	Category of injury	Participants	Intervention	Control	Outcome measures	Results and conclusions
Christakou et al., 2007	Non-surgical	Grade II ankle sprain	Active young athletes (n=20, 18 to 30 y, 3 women and 17 men)	MI plus SR, 3 d·wk^{-1} during 12 wk (n=10)	SR, 3 d·wk^{-1} during 12 wk (n=10)	Muscular endurance, functional stability and dynamic balance	MI had several positive effects on the functional rehabilitation of grade II ankle sprains
Hoyek et al., 2014	Non-surgical	Shoulder impingement syndrome (stage II)	Adult patients between 35 to 65 y (n=16, 46.3±9.0 y, 8 women and 8 men)	MI plus SR, 3 d·wk^{-1} during 10 sessions (n=8)	SR, 3 d·wk^{-1} during 10 sessions (n=8)	ROM (glenohumeral joint) in flexion, extension, abduction, adduction, medial rotation and lateral rotation.	MI may help in enhancing shoulder mobility in a stage II impingement syndrome.
Nunes et al., 2015	Non-surgical	Acute lateral ankle sprain	Young soccer men athletes (n=20, 16 to 20 y)	MI plus SR, 5 d·wk^{-1} (n=10)	SR, 5 d·wk^{-1} (n=10)	ROM in ankle plantar and dorsal flexion, dynamic balance and functional stability.	MI was not an effective method for treating ankle sprains in field soccer athletes to improve ROM, dynamic balance and functional stability.

Rostami et al., 2013	Non-surgical	Hand orthopaedic injuries	Patients with active ROM impairments (n=30, 38 y, 22 women and 8 men)	VMF plus SR, 5 d·wk^{-1} during 3 wk (n=8)	SR, 5 d·wk^{-1} during 3 wk (n=8)	Total active ROM (sum of the angles formed by the metacarpophalangeal, proximal interphalangeal and distal interphalangeal joints)	Adding VMF to SR was effective for early and maximum improvement of motor recovery in the patients with orthopaedic injuries.
Başkaya et al., 2018	Non-surgical	Adhesive capsulitis	Adults patients (n=30, 56.6±9.5 y, 21 women and 9 men)	VMF plus SR, 10 sessions (n=8)	SR plus same VMF exercises without mirror, 10 sessions (n=8)	Active and passive ROM (glenohumeral joint) in flexion, abduction, internal and external rotation.	VMF plus SR showed an improvement of shoulder joint ROM
Cupal & Brewer, 2001	Surgical	Arthroscopic ACL reconstruction	Adults patients (n=30, 28.2±8.2 y, 14 women and 16 men)	Relaxation and MI plus SR, 10 sessions (n=10)	-Control: SR (n=10) -Placebo: Sham MI-peaceful scene visualization plus SR (n=10)	Knee strength	Relaxation and MI may be beneficial to ACL rehabilitation
Mayer et al., 2005	Surgical	Total hip replacement	Adults and elder patients (n=24, 40 to 85 y, 15 women and 9 men)	MI (mental walking training) plus SR, 3 d·wk^{-1} during 3 wk (n=13)	SR, 3 d·wk^{-1} during 3 wk (n=11)	Quantitative gait variables (walking speed, stride length and stance phase percentage)	The MI showed relevant improvements in quantitative gait variables with respect to the control group

Moukarzel, et al., 2017	Surgical	Knee arthroplasty	Elder patients (n=20, 65 to 75 y, 16 women and 4 men)	MI plus SR, 3 d·wk^{-1} during 4 wk (n=10)	SR, 3 d·wk^{-1} during 4 wk (n=10)	Quadriceps strength, active and passive ROM (flexion and extension) and functional mobility	MI might be relevant to promote motor relearning and recovery after total knee arthroplasty
Mahmoud, et al., 2016	Surgical	Total knee replacement (secondary to osteoarthritis)	Adults and elder patients (n=10, 50 to 8 y, 6 women and 4 men)	MI plus SR, 3 d·wk^{-1} during 8 wk (n=4)	SR, 3 d·wk^{-1} during 8 wk (n=6)	Knee ROM	MI group showed a greater increase in knee ROM when compared to the control.
Marusic et al., 2018	Surgical	Hip arthroplasty	Elder patients (n=21, 7 women and 14 men)	MI + AO plus SR, 3 d·wk^{-1} during 8 wk (n=10, 64.4±4.1 y)	SR, 3 d·wk^{-1} during 8 wk (n=11, 63.1±5.6 y)	Functional mobility	Results showed that the integrated AO+ MI approach was an efficient tool to enhance the functional rehabilitation outcomes of postsurgical orthopaedic patients

Paravlic et al., 2019	Surgical	Knee arthroplasty	Adult and elder patients (n=34, 50 to 85 y, 15 women and 19 men)	MI focused on maximal isometric knee extension strength plus SR, 5 d·wk^{-1} during 4 wk (n=17)	SR, 3 d·wk^{-1} during 4 wk (n=17)	Maximal isometric knee extension strength, gait measurements and functional variables	MI when added to RS, led to improvements in multiple measures of patients' physical functional capabilities
Pawar et al., 2019	Surgical	Wrist complex injuries	Adult patients (n=40, 30 to 40 y, 21 women and 19 men)	VMF, 5 d·wk^{-1} during 4 wk (n=20)	Bilateral approach, 5 d·wk^{-1} during 4 wk (n=20)	Wrist and fingers active ROM	There was no significant difference between bilateral approach and VMF
Belleli et al., 2010	Surgical	Orthopaedic patients (hip fracture or hip or knee replacement)	Patients (n=60, 18 to 90 y, 21 women and 19 men)	AO plus SR, 6 d·wk^{-1} during 3 wk (n=30)	SR, 6 d·wk^{-1} during 3 wk (n=30)	Functional independence measure	In addition to SR, AO was effective in the rehabilitation of postsurgical orthopaedic patients
Park et al., 2014	Surgical	Total knee replacement	Patients (n=18, 18 to 90 y, 21 women and 19 men)	AO plus SR, 3 d·wk^{-1} during 3 wk (n=9)	SR, 3 d·wk^{-1} during 3 wk (n=9)	Knee joint function and balance	AO training is considered conducive to improving knee functions in patients with total knee replacement

Villafañe et al., 2017	Surgical	Total knee replacement	Adult and elder patients (n=31, 18 to 90 y, 21 women and 10 men)	AO plus SR, 5 $d \cdot wk^{-1}$ (twice) during 2 wk (n=14, 70.4±7.5)	Sham AO (nature video) plus SR, 5 $d \cdot wk^{-1}$ (twice) during 2 wk (n=17, 70.1±7.7)	Active and passive knee ROM	Adding AO training to SR is associated with a greater degree of recovery in patients who have undergone a primary total knee replacement
Villafañe et al., 2016	Surgical	Hip arthroplasty	Adult and elder patients (n=24, 50 to 90 y, 21 women and 10 men)	AO plus SR, 5 $d \cdot wk^{-1}$ (twice) during 10 sessions (n=14, 70.4±7.5)	SR, 5 $d \cdot wk^{-1}$ (twice) during 10 sessions (n=17, 70.1±7.7)	Active and passive hip ROM	Both interventions were effective improving hip ROM
Bayón-Calatayud et al., 2016	Surgical	Distal radial fractures	Adult patients (n=22, 15 women and 7 men)	Daily VMF during 15 sessions plus SR (n=11, 61.0±13.0)	SR (n=11, 55.3±18.2)	Active wrist extension ROM	VMF was not superior to conventional occupational therapy in wrist extension ROM

Abolfazli et al., 2018	Surgical	Hand reconstructive surgery	Adult patients (n=40, 15 women and 25 men)	VMF plus SR, 2 d·wk^{-1} during 8 wk (n=20, 30.4±9.4)	SR, 2 d·wk^{-1} during 8 wk (n=20, 33.3±11.4)	Active ROM and grip strength	VMF plus SR showed greater improvements in ROM compared with the SR but not in the grip strength
Frenkel et al., 2018	Surgical	Total knee endoprosthesis	Adult and elder patients (n=40, 62.5±9.6, 17 women and 23 men)	VMF + MI plus SR, 5 sessions for 12 days (n=20)	SR, 5 sessions for 12 days (n=20)	ROM (Knee joint) in flexion and ability to walk	VMF + MI plus SR showed greater improvements in ROM and ability to walk compared with the SR
Harput et al., 2018	Surgical	ACL reconstruction	Adult patients (n=48, 29.5±.8,5 women and 25 men)	-Concentric CE plus SR, 3 d·wk^{-1} during 8 wk (n=16) -Eccentric CE plus SR, 3 d·wk^{-1} during 8 wk (n=16)	SR during 8 wk (n=16)	Isometric MVC (quadriceps)	Both CE forms improved post-surgical quadriceps strength
Papandreou et al., 2012	Surgical	ACL reconstruction	Young patients (n=42, 20 to 25 y)	-CE plus SR, 3 d·wk^{-1} during 8 wk (n=14) -CE plus SR, 5 d·wk^{-1} during 8 wk (n=14)	SR during 8 wk (n=14)	Quadriceps muscle strength	Both CE showed greater strength improvement in comparison to SR in isolation

Zult et al., 2018	Surgical	ACL reconstruction	Adult patients (n=43, 18 to 60 y)	CE plus SR, 12 wk (n=22, 28±9)	SR, 12 wk (n=21, 28±10)	Maximal strength and single leg hop distance	CE did not improve rehabilitation outcomes

MI: Motor imagery; ROM: Range of movement; CE: Cross-education; MVC: Maximal voluntary contractions; C-SA: Cross-sectional area; y: years; d·wk^{-1}: days per week; EMG: electromyography; h·day^{-1}: hours per day; 1-RM, 1 repetition maximum; PT: Physical therapy; SR: Standard rehabilitation; VMF: Visual mirror feedback; ACL: Anterior cruciate ligament; AO: Action observation

FIGURE CAPTIONS

Figure 1. PRISMA Flow Diagram.

Figure 1. Flow chart of studies selection according to PRISMA

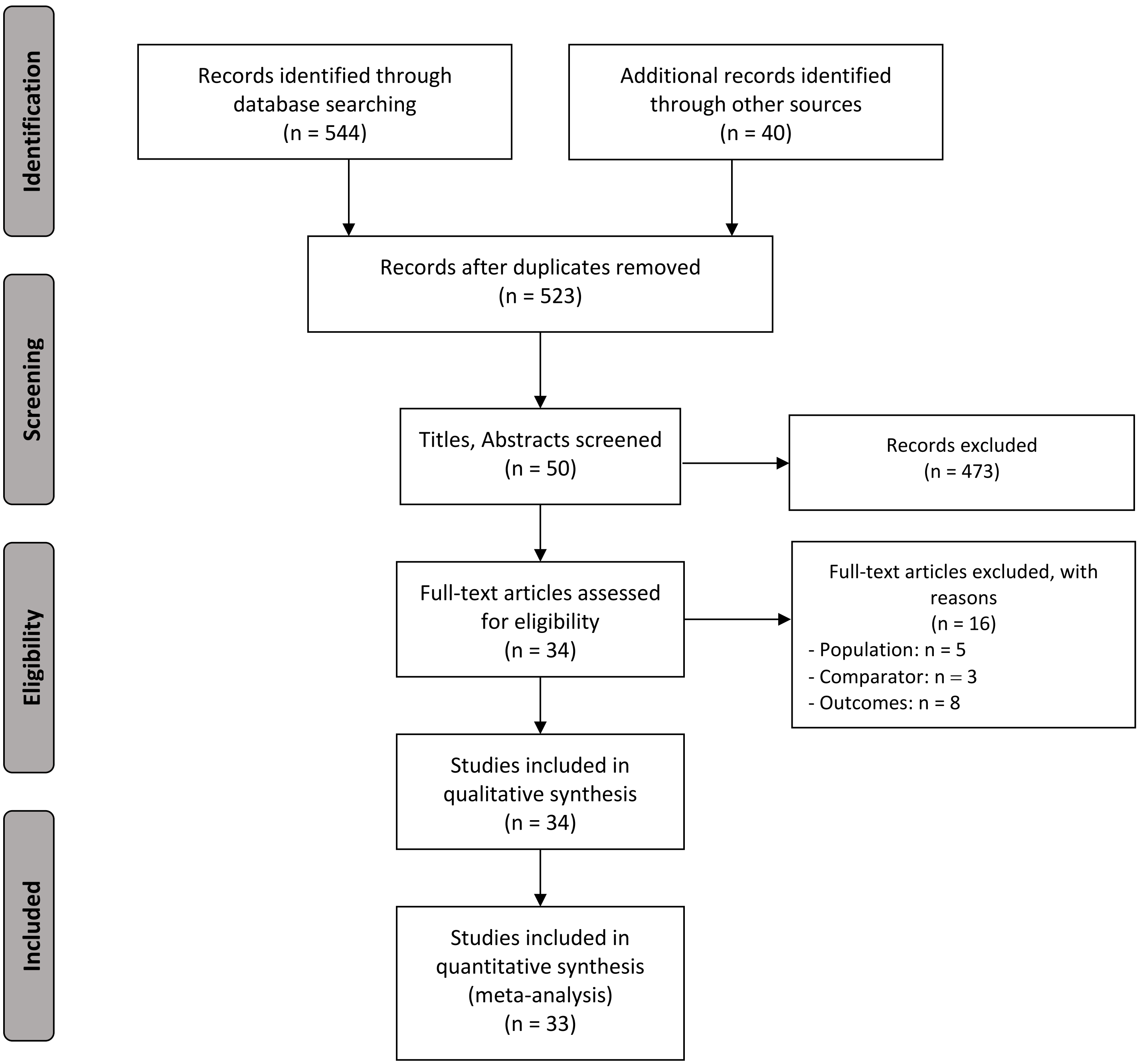


Figure 2. Risk of bias summary. Review authors' judgements about each risk of bias item for each included study (Risk of Bias scale).

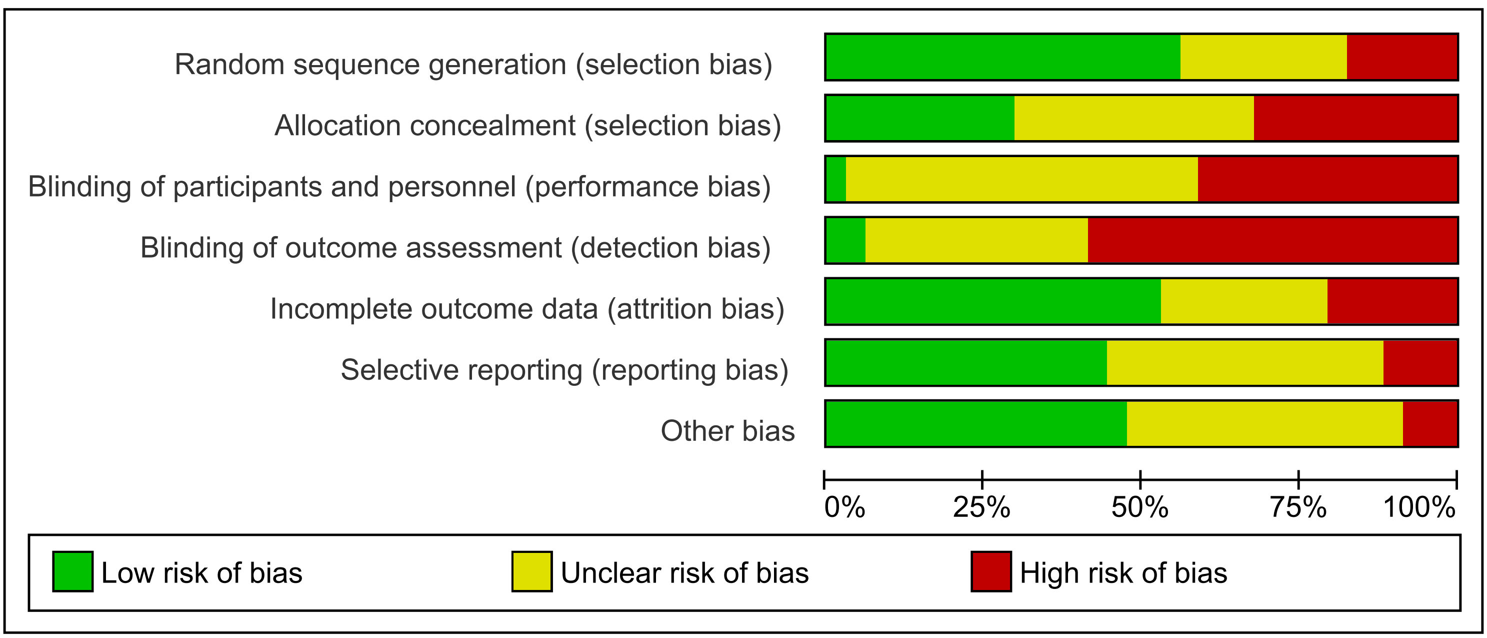
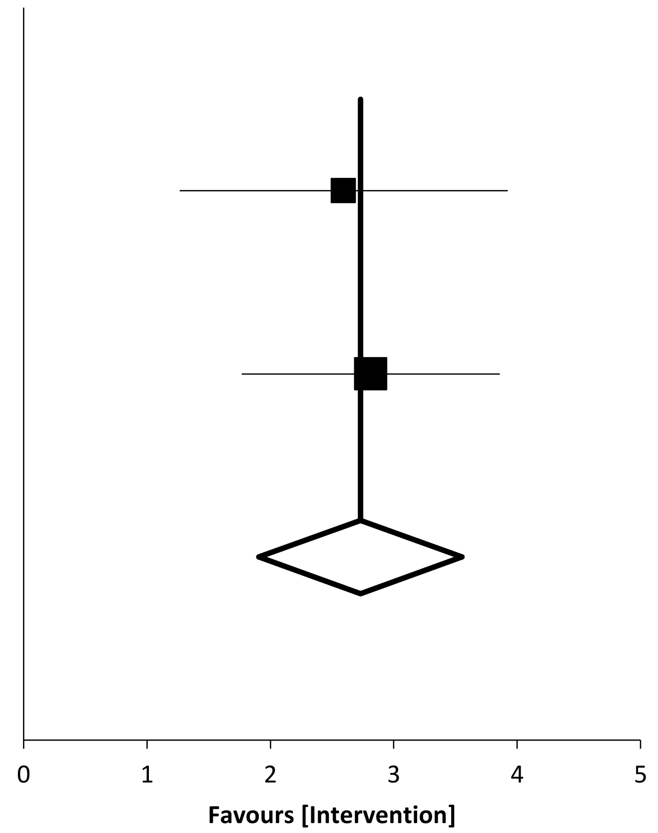

Random sequence generation (selection bias)
Allocation concealment (selection bias)
Blinding of participants and personnel (performance bias)
Blinding of outcome assessment (detection bias)
Incomplete outcome data (attrition bias)
Selective reporting (reporting bias)
Other bias
0%
25%
50%
75%
100%
Low risk of bias
Unclear risk of bias
High risk of bias

Figure 3. Risk of bias graph. Review authors' judgements about each risk of bias item presented as percentages across all included studies (Risk of Bias scale).

	Random sequence generation (selection bias)	Allocation concealment (selection bias)	Blinding of participants and personnel (performance bias)	Blinding of outcome assessment (detection bias)	Incomplete outcome data (attrition bias)	Selective reporting (reporting bias)	Other bias
Abolfazli et al., 2018	+	+	?	−	?	?	+
Andrushko et al., 2018	+	?	?	−	+	+	+
Baskaya et al., 2018	?	?	?	−	+	−	+
Bayón-Calatayud et al., 2016	+	+	?	?	+	?	+
Belleli et al., 2010	+	?	?	−	+	+	+
Christankou et al., 2007	+	−	−	−	−	−	?
Clark et al., 2014	?	?	−	?	−	−	?
Cupal & Brewer, 2001	+	−	−	−	+	?	?
Dilek et al., 2017	+	+	?	−	+	+	+
Eindiedel et al., 2011	−	?	−	?	?	?	−
Farthing et al., 2009	−	−	−	?	?	?	+
Farthing et al., 2011	−	−	?	−	?	?	?
Frenkel et al., 2014	?	?	+	−	+	+	?
Frenkel et al., 2018	+	?	?	?	+	?	+
Harput et al., 2018	?	+	?	?	+	+	?
Koyek et al., 2014	+	?	−	−	?	+	?
Magnus et al., 2010	?	−	?	−	+	?	?
Magnus et al., 2013	+	+	?	?	+	+	+
Mahmoud et al., 2016	?	−	−	−	−	?	−
Marusic et al., 2018	+	+	?	−	+	+	?
Mayer et al., 2005	+	?	−	−	?	?	+
Moukarzel et al., 2017	+	+	−	−	+	?	+
Newsom et al., 2003	?	−	?	−	−	?	?
Nunes et al., 2015	+	?	?	−	+	+	+
Papandreou et al., 2012	+	+	?	+	+	+	?
Paravlic et al., 2019	+	−	−	?	−	−	?
Park et al., 2014	+	−	−	?	−	+	+
Pawar et al., 2019	−	−	−	−	−	?	−
Pearce et al., 2012	−	?	?	−	?	?	?
Rostami et al., 2013	+	+	?	−	+	?	+
Stenekes et al., 2009	?	?	−	?	?	+	+
Villafañe et al., 2016	−	−	−	?	?	+	+
Villafañe et al., 2017	+	?	?	+	+	+	?
Zult et al., 2018	?	+	?	?	+	+	?

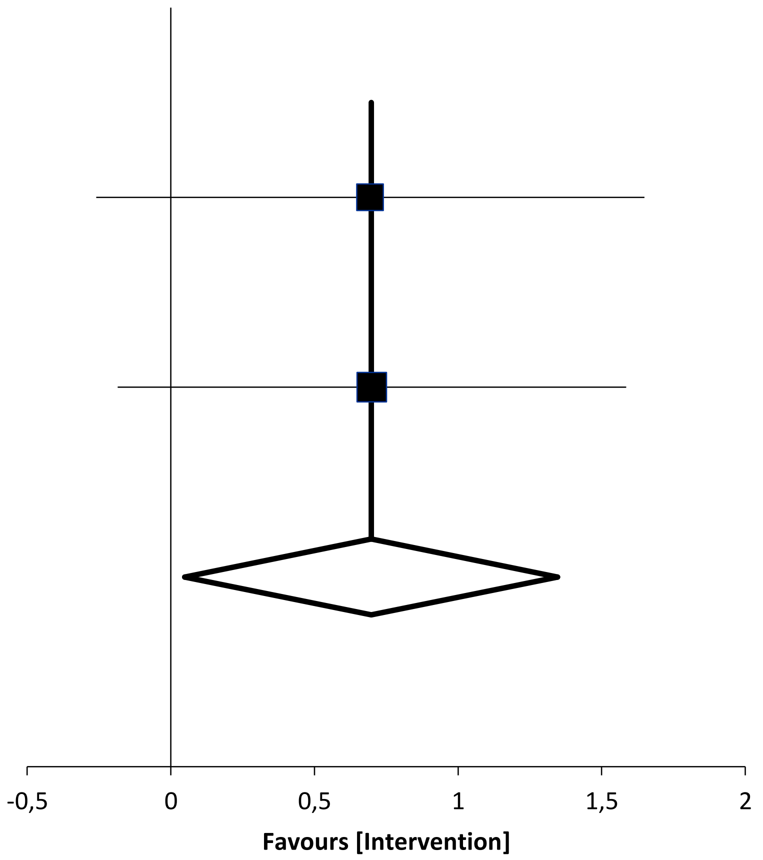
Figure 4. Synthesis forest plot. This forest plot summarizes the results of included studies (sample size, standardized mean differences [SMDs], and weight). The small boxes with the squares represent the point estimate of the effect size and sample size. The lines on either side of the box represent a 95% confidence interval (CI). A. Forest plot for experimental immobilization studies that used motor imagery intervention on strength outcome. B. Forest plot for experimental immobilization studies that used motor imagery intervention on range of motion outcome. C. Forest plot for experimental immobilization studies that used cross-education intervention on strength outcome. D. Forest plot for surgery immobilization studies that used motor imagery intervention on strength outcome.

Author (year)	Sample size	Measure (CI)	Weight %
Newsom (2013)	17	2.59 (1.26; 3.92)	38.21%
Clark (2014)	29	2.81 (1.77; 3.86)	61.79%
Synthesis low	46	2.73 (1.91; 3.55)	100%



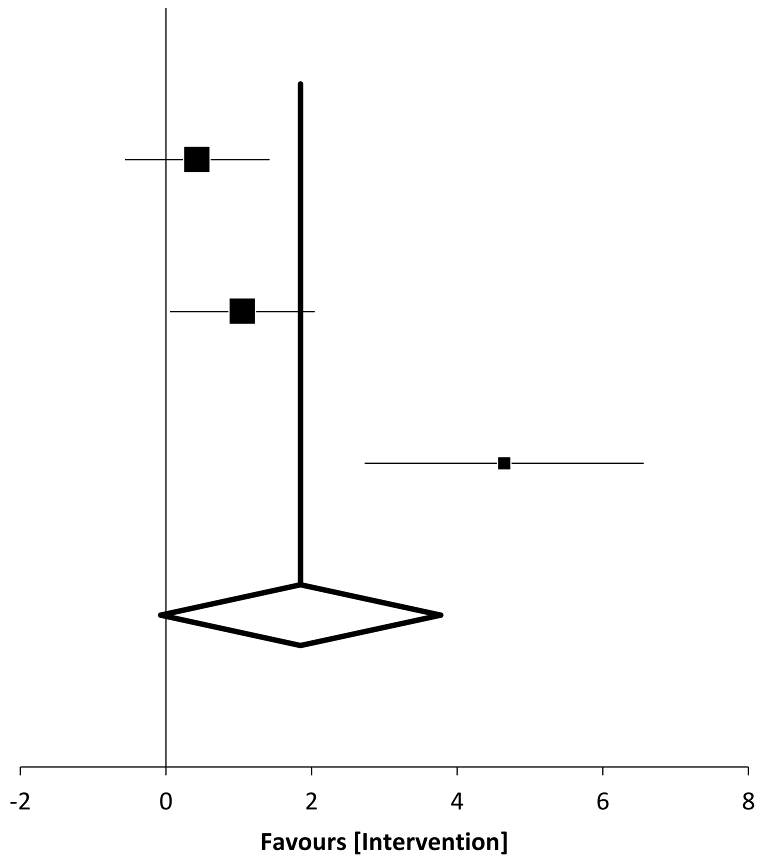
A.

Author (year)	Sample size	Measure (CI)	Weight %
Frenkel (2014)	18	0.69 (-0.26; 1.65)	46.2%
Einsiedel (2011)	21	0.7 (-0.18; 1.59)	53.8%
Synthesis low	39	0.7 (0.05; 1.35)	100%



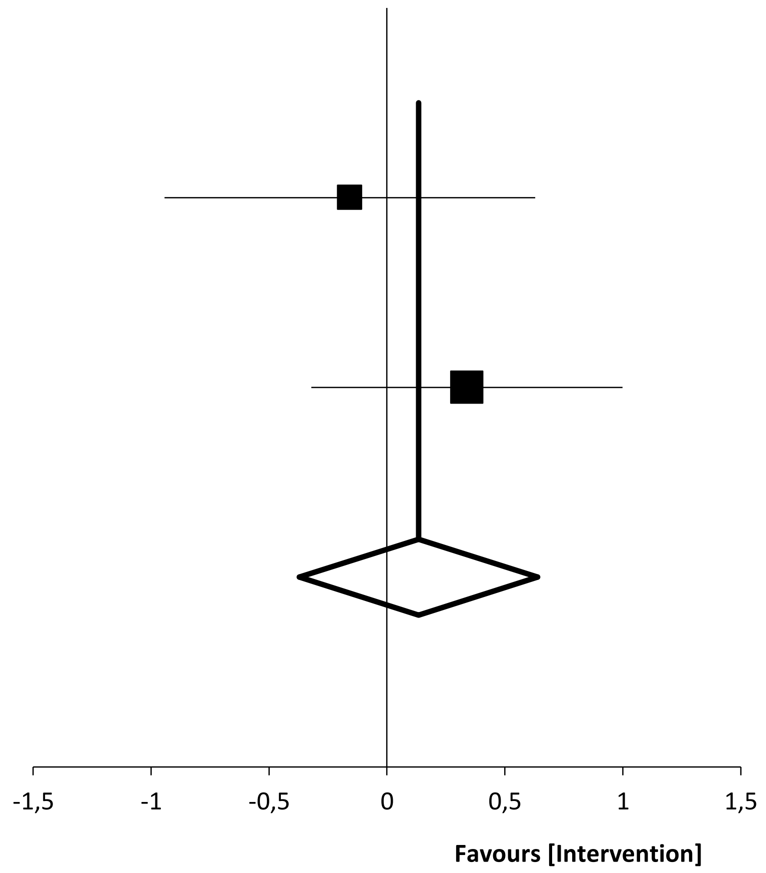
B.

Author (year)	Sample size	Measure (CI)	Weight %
Andrushko (2018)	16	0.43 (-0.56; 1.42)	35.8%
Pearce (2012)	18	1.05 (0.06; 2.05)	35.8%
Magnus (2010)	17	4.65 (2.73; 6.56)	28.4%
Synthesis low	51	1.85 (-0.07; 3.77)	100%



C.

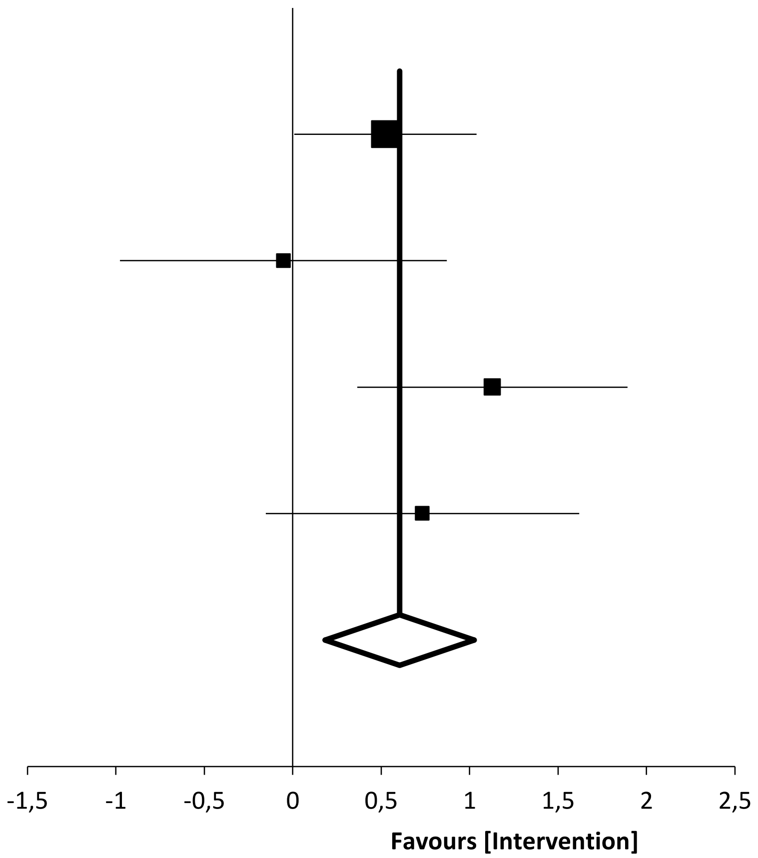
Author (year)	Sample size	Measure (CI)	Weight %
Stenekes (2009)	25	-0.16 (-0.94; 0.63)	41.3%
Dilek (2017)	36	0.34 (-0.32; 1)	58.7%
Synthesis low	61	0.13 (-0.37; 0.64)	100%



D.

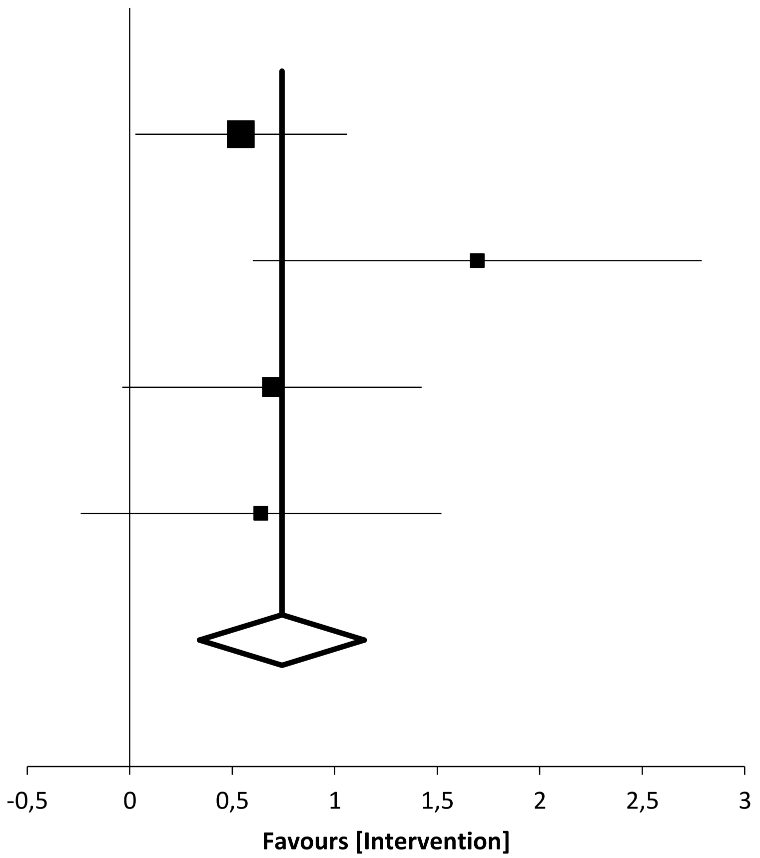
Figure 5. Synthesis forest plot. This forest plot summarizes the results of included studies (sample size, standardized mean differences [SMDs], and weight). The small boxes with the squares represent the point estimate of the effect size and sample size. The lines on either side of the box represent a 95% confidence interval (CI). A. Forest plot for surgery studies that used action observation intervention on balance outcome. B. Forest plot for surgery studies that used action observation intervention on functional status outcome. C. Forest plot for surgery studies that used visual mirror feedback intervention on range of motion outcome. D. Forest plot for surgery studies that used cross-education intervention on strength outcome.

Author (year)	Sample size	Measure (CI)	Weight %
Bellelli (2010)	60	0.52 (0.01; 1.04)	40.66%
Park (2014)	18	-0.05 (-0.98; 0.87)	17.31%
Villafañe (2016)	31	1.13 (0.36; 1.89)	23.47%
Villafañe (2017)	23	0.73 (-0.15; 1.62)	18.55%
Synthesis low	132	0.61 (0.18; 1.03)	100%



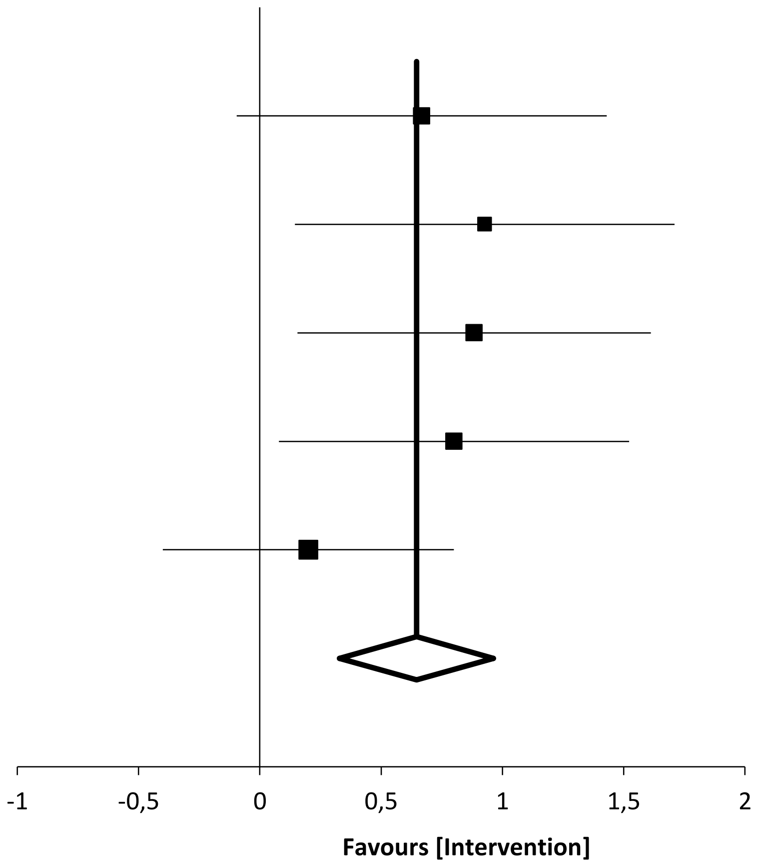
A.

Author (year)	Sample size	Measure (CI)	Weight %
Bellelli (2010)	60	0.54 (0.03; 1.06)	43.74%
Park (2014)	18	1.7 (0.6; 2.79)	12.41%
Villafañe (2016)	31	0.69 (-0.04; 1.42)	25.42%
Villafañe (2017)	23	0.64 (-0.24; 1.52)	18.43%
Synthesis low	132	0.74 (0.34; 1.14)	100%



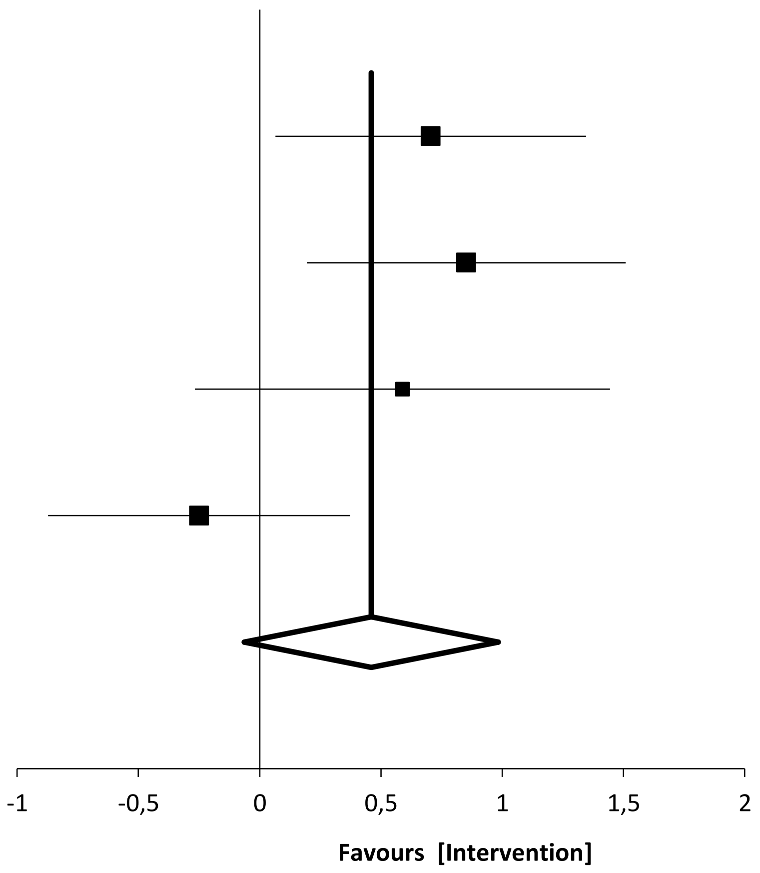
B.

Author (year)	Sample size	Measure (CI)	Weight %
Papandreou (2012 a)	28	0.67 (-0.1; 1.43)	17.3%
Papandreou (2012 b)	28	0.93 (0.14; 1.71)	16.43%
Harput (2018 a)	32	0.88 (0.16; 1.61)	18.98%
Harput (2018 b)	32	0.8 (0.08; 1.52)	19.3%
Zult (2018)	43	0.2 (-0.4; 0.8)	27.99%
Synthesis low	163	0.65 (0.33; 0.96)	100%



C.

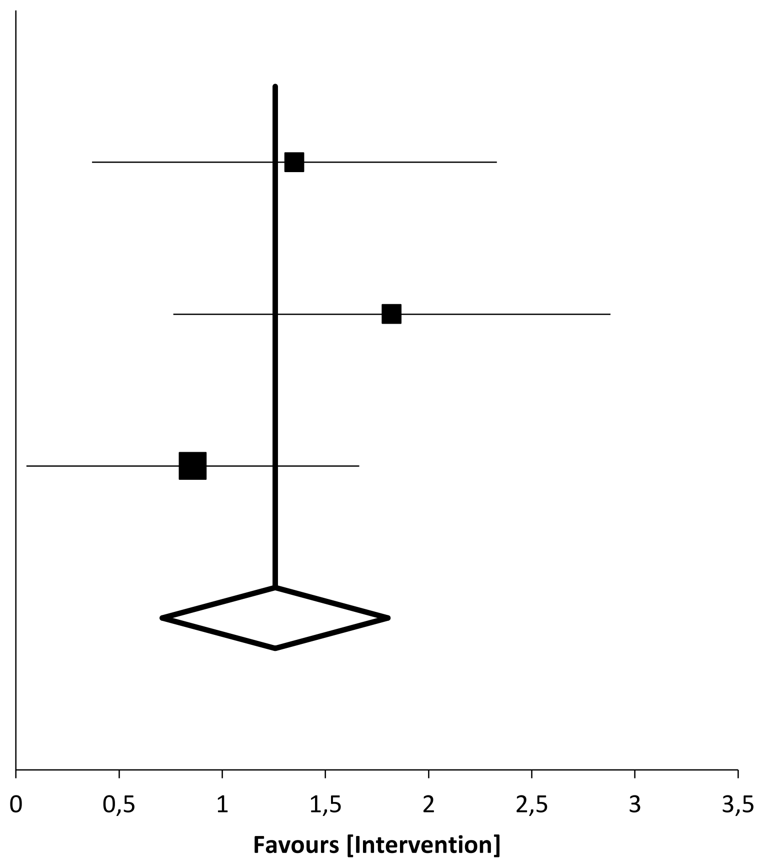
Author (year)	Sample size	Measure (CI)	Weight %
Albolfazli (2018)	40	0.71 (0.07; 1.34)	26.58%
Frenkel (2018)	39	0.85 (0.19; 1.51)	26.01%
Bayon-Calatayud (2016)	22	0.59 (-0.27; 1.44)	20.25%
Pawar (2019)	40	-0.25 (-0.87; 0.37)	27.16%
Synthesis low	141	0.46 (-0.06; 0.98)	100%



D.

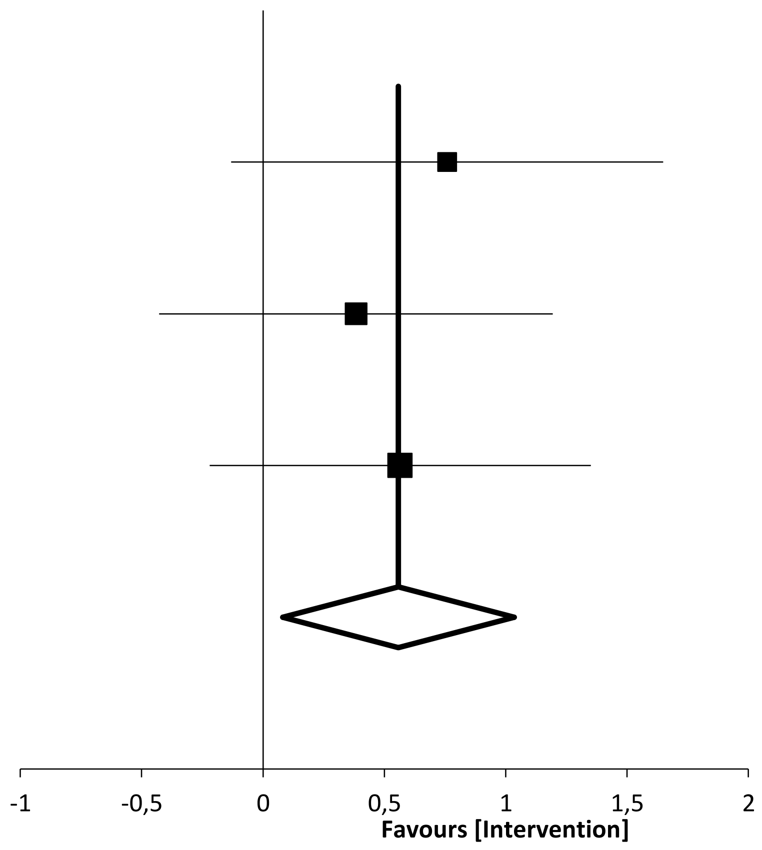
Figure 6. Synthesis forest plot. This forest plot summarizes the results of included studies (sample size, standardized mean differences [SMDs], and weight). The small boxes with the squares represent the point estimate of the effect size and sample size. The lines on either side of the box represent a 95% confidence interval (CI). A. Forest plot for surgery studies that used motor imagery intervention on strength outcome. B. Forest plot for surgery studies that used motor imagery intervention on walking speed outcome. C. Forest plot for surgery studies that used motor imagery intervention on range of motion outcome.

Author (year)	Sample size	Measure (CI)	Weight %
Cupal (2001)	20	1.35 (0.37; 2.33)	30.11%
Moukarzel (2017)	20	1.82 (0.76; 2.88)	25.94%
Paravlic (2019)	26	0.86 (0.05; 1.66)	43.95%
Synthesis low	66	1.26 (0.71; 1.8)	100%



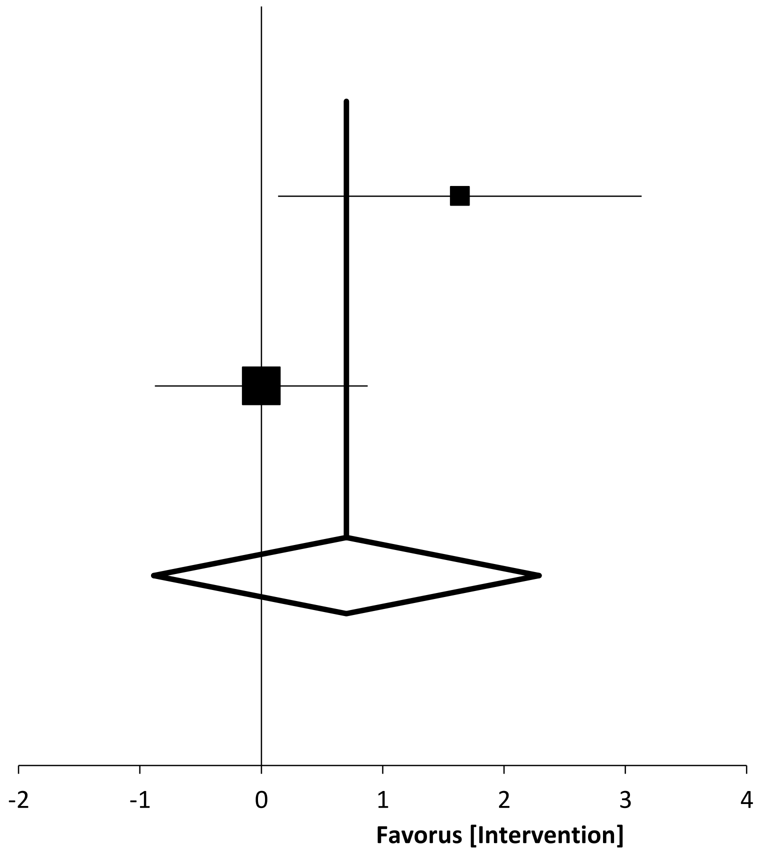
A.

Author (year)	Sample size	Measure (CI)	Weight %
Marusic (2018)	21	0.76 (-0.13; 1.65)	28.67%
Mayer (2005)	24	0.38 (-0.43; 1.19)	34.52%
Paravlic (2019)	26	0.57 (-0.22; 1.35)	36.81%
Synthesis low	71	0.56 (0.08; 1.03)	100%



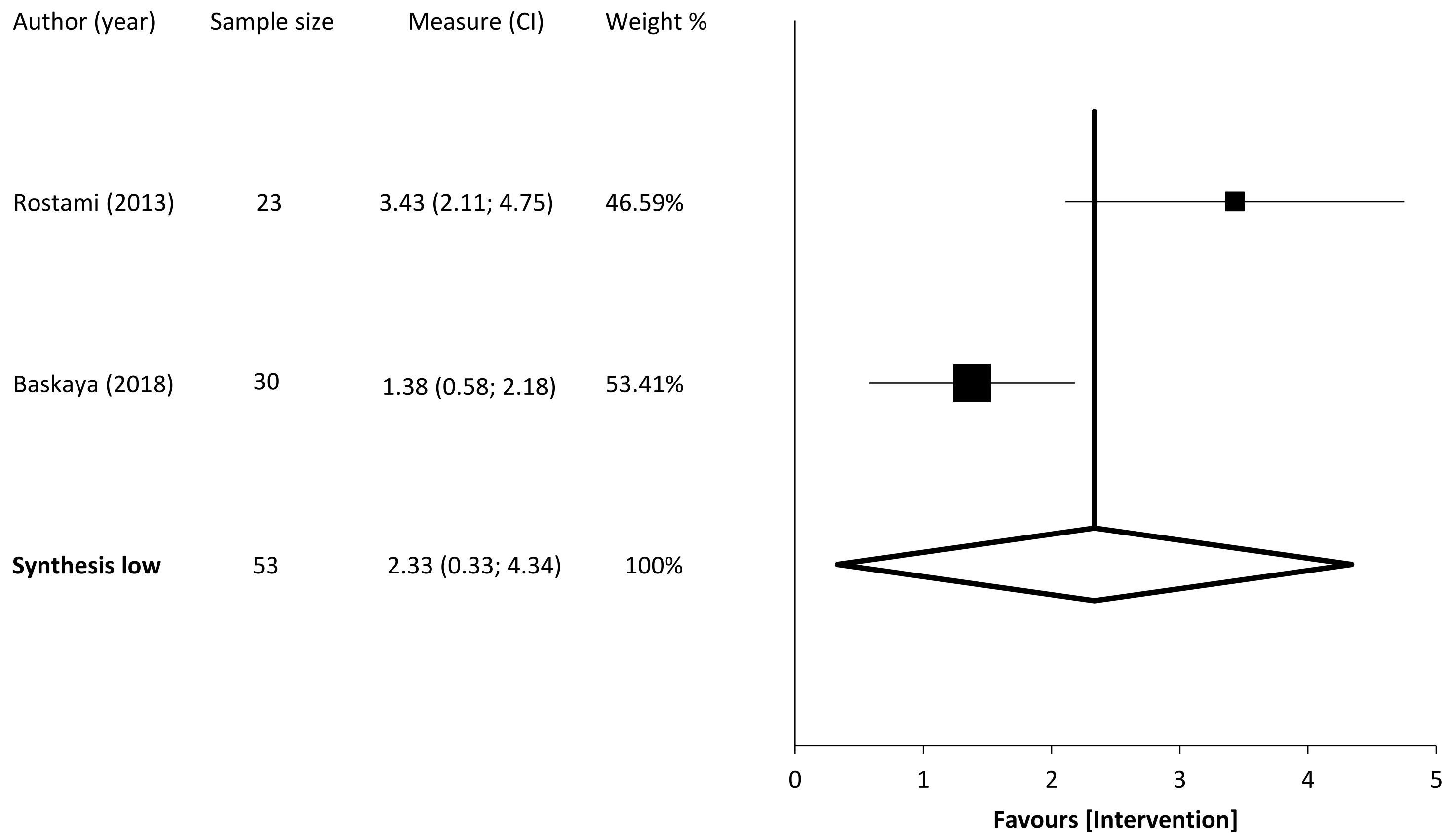
B.

Author (year)	Sample size	Measure (CI)	Weight %
Mahmoud (2016)	10	1.64 (0.14; 3.13)	42.83%
Moukarzel (2017)	20	0 (-0.88; 0.88)	57.17%
Synthesis low	30	0.7 (-0.89; 2.29)	100%

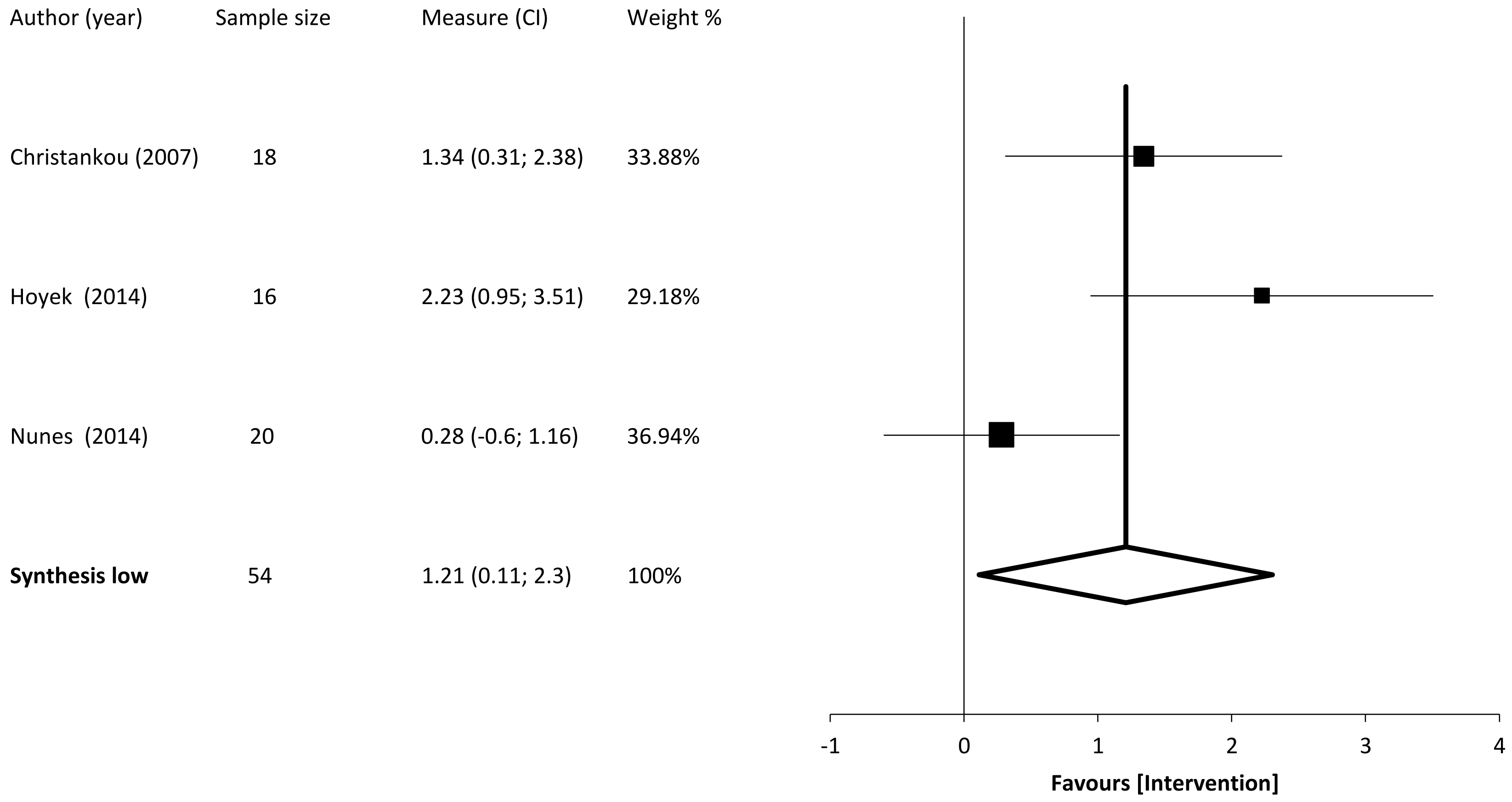


C.

Figure 7. Synthesis forest plot. This forest plot summarizes the results of included studies (sample size, standardized mean differences [SMDs], and weight). The small boxes with the squares represent the point estimate of the effect size and sample size. The lines on either side of the box represent a 95% confidence interval (CI). A. Forest plot for injury studies that used visual mirror feedback intervention on range of motion outcome. B. Forest plot for injury studies that used motor imagery intervention on range of motion outcome.


Author (year)
Sample size
Measure (CI)
Weight %
Rostami (2013)
23
3.43 (2.11; 4.75)
46.59%
Baskaya (2018)
30
1.38 (0.58; 2.18)
53.41%
Synthesis low
53
2.33 (0.33; 4.34)
100%
0
1
2
3
4
5
Favours [Intervention]

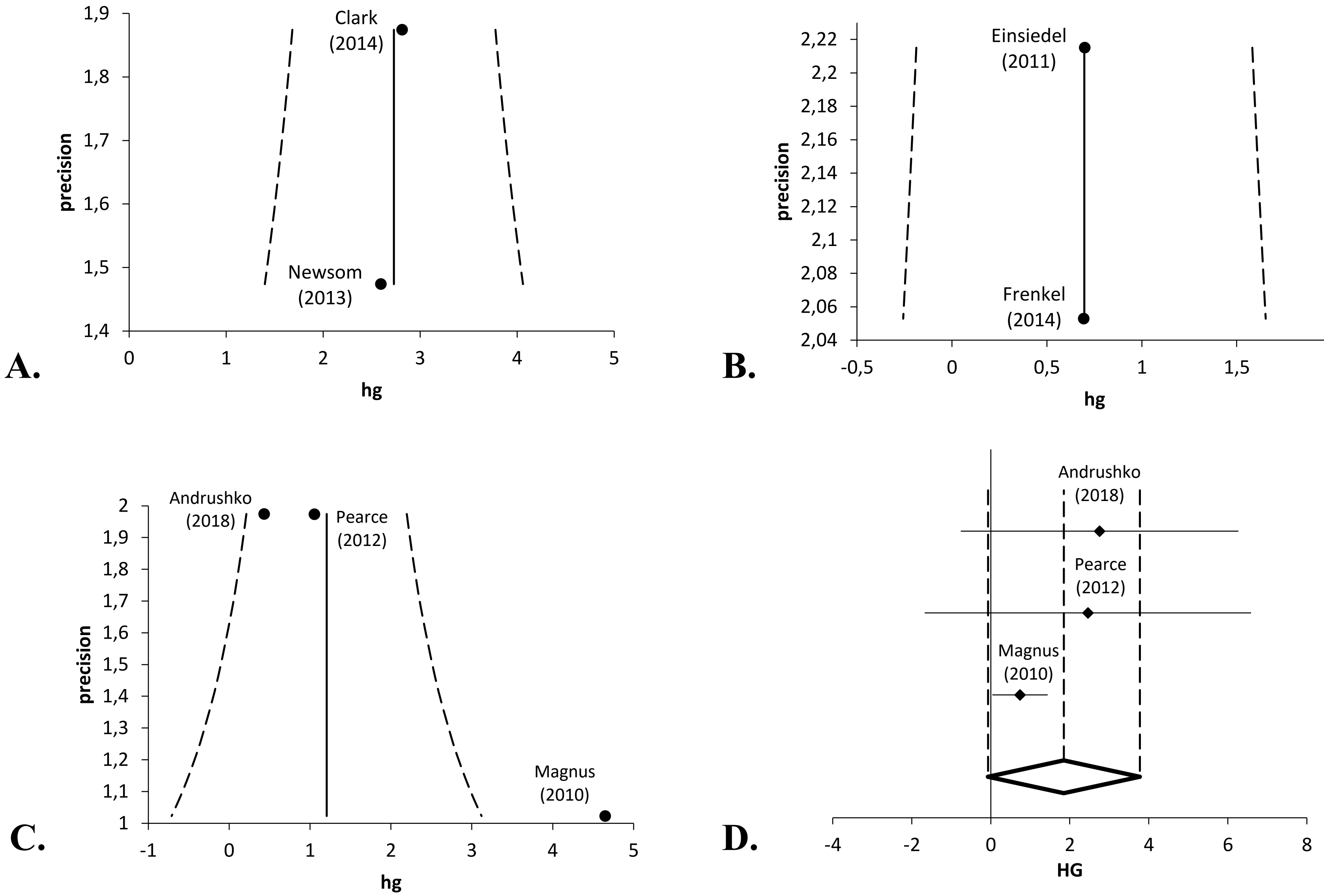
A.


Author (year)
Sample size
Measure (CI)
Weight %
Christankou (2007)
18
1.34 (0.31; 2.38)
33.88%
Hoyek (2014)
16
2.23 (0.95; 3.51)
29.18%
Nunes (2014)
20
0.28 (-0.6; 1.16)
36.94%
Synthesis low
54
1.21 (0.11; 2.3)
100%
-1
0
1
2
3
4
Favours [Intervention]

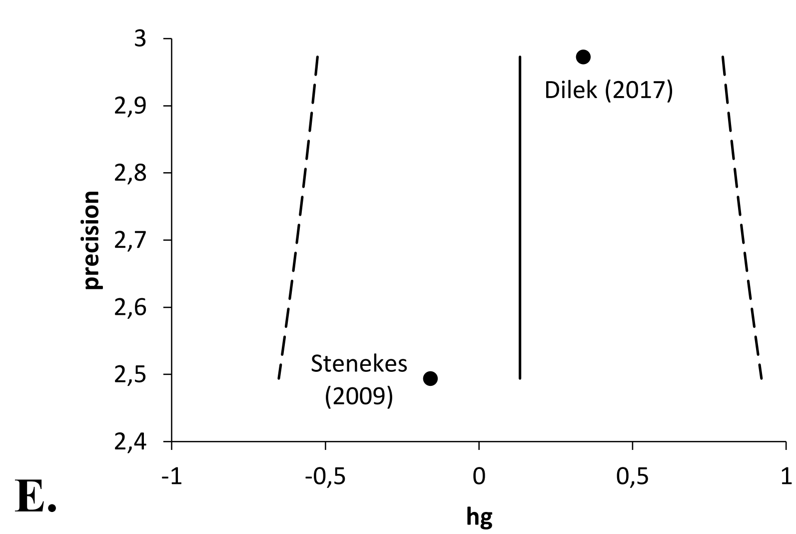
B.

Annex 1. Publication bias heterogeneity funnel plots and exclusion sensitivity plots. The diagonal lines represent the 95% confidence limits. SMD: standardized mean difference. A. Funnel plot for experimental immobilization studies that used motor imagery intervention on strength outcome. B. Funnel plot for experimental immobilization studies that used motor imagery intervention on range of motion outcome. C. Funnel plot for experimental immobilization studies that used cross-education intervention on strength outcome. D. Exclusion sensitivity plot for experimental immobilization studies that used cross-education intervention on strength outcome. E. Funnel plot for surgery immobilization studies that used motor imagery intervention on strength outcome. F. Funnel plot for surgery studies that used action observation intervention on balance outcome. G. Exclusion sensitivity plot for surgery studies that used action observation intervention on balance outcome. H. Funnel plot for surgery studies that used action observation intervention on functional status outcome. J. Funnel plot for surgery studies that used visual mirror feedback intervention on range of motion outcome. I. Exclusion sensitivity plot for surgery studies that used visual mirror feedback intervention on range of motion outcome. K Funnel plot for surgery studies that used cross-education intervention on strength outcome. L. Funnel plot for surgery studies that used motor imagery intervention on strength outcome. M. Funnel plot for surgery studies that used motor imagery intervention on walking speed outcome. N. Exclusion sensitivity plot for surgery studies that used motor imagery intervention on walking speed outcome. Q. Funnel plot for surgery studies that used motor imagery intervention on range of motion outcome. P. Funnel plot for injury studies that used visual mirror feedback intervention on range of motion outcome. Q. Funnel plot for injury studies that used motor imagery intervention on range of motion outcome. R. Exclusion sensitivity plot for injury studies that used motor imagery intervention on range of motion outcome.

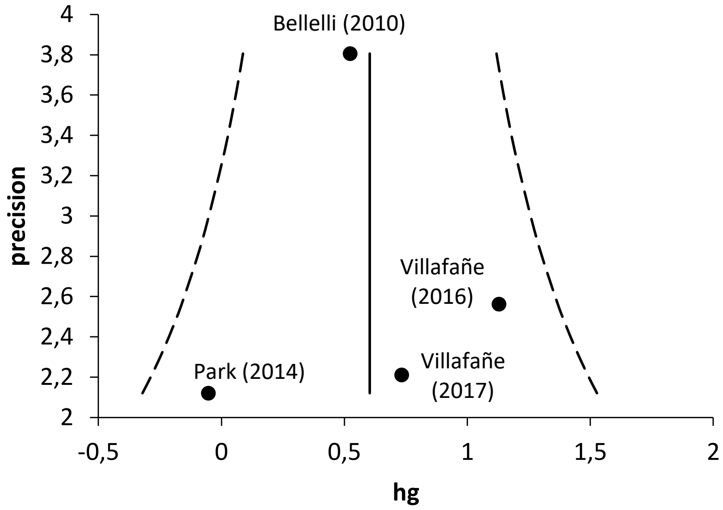
Experimental Immobilization



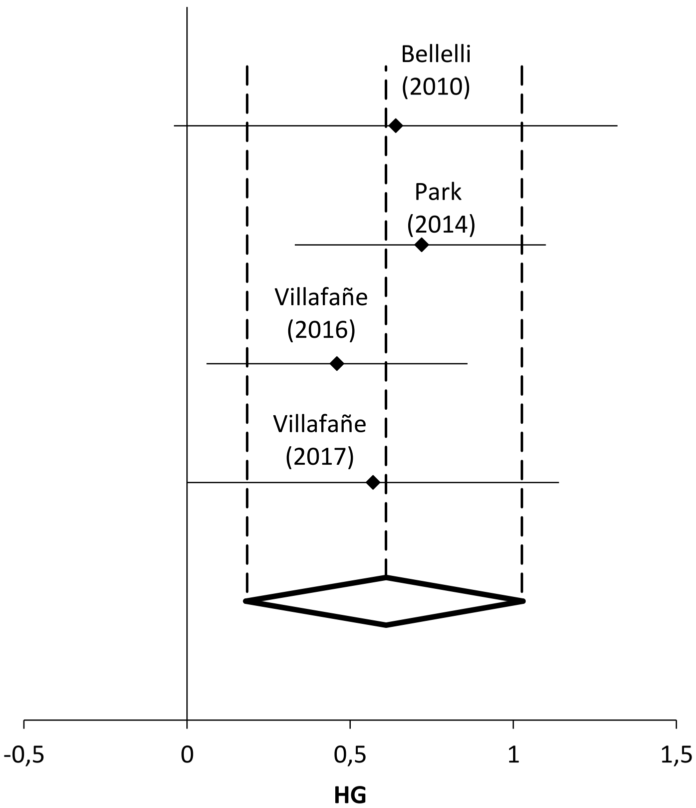
Surgery Immobilization



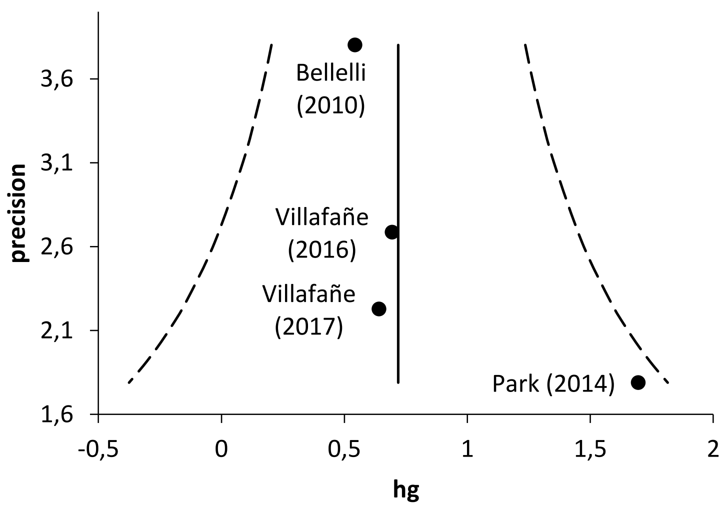
No immobilization: Surgery



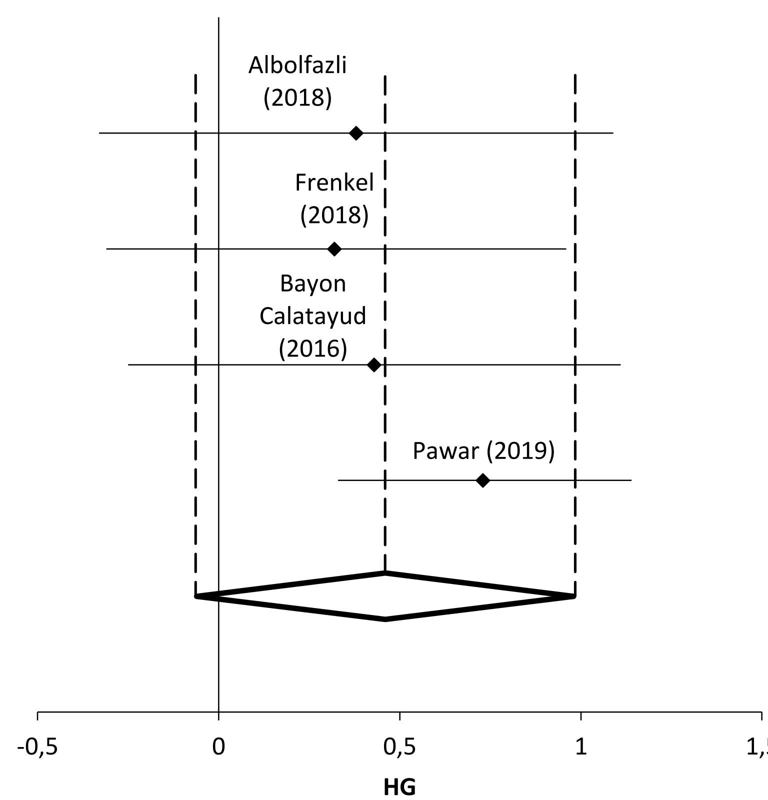
F.



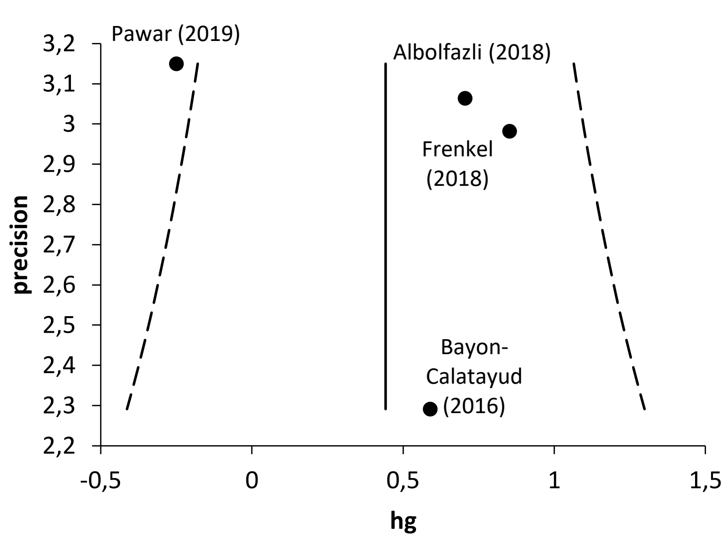
G.



H.

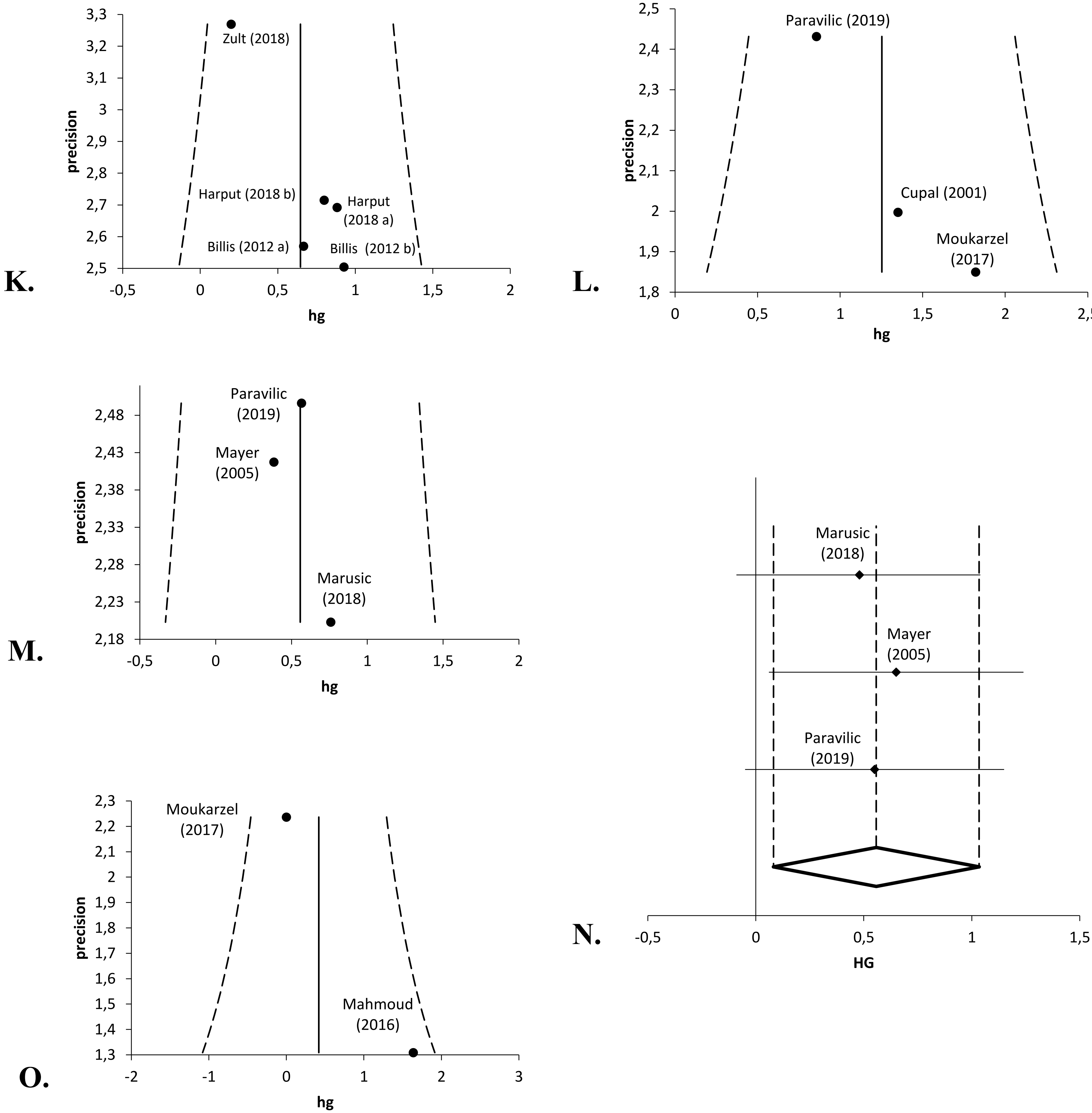


I.

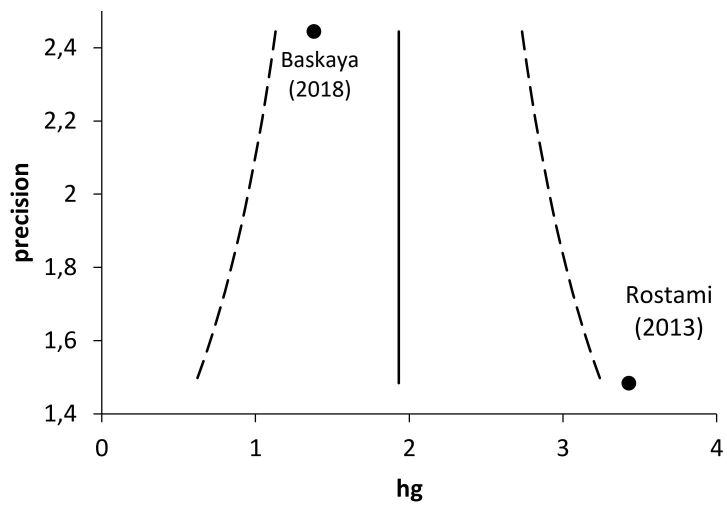


J.

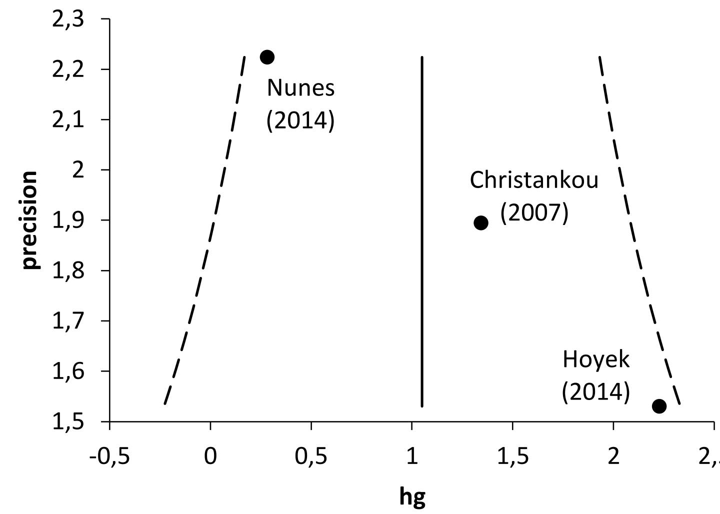
No immobilization: Surgery



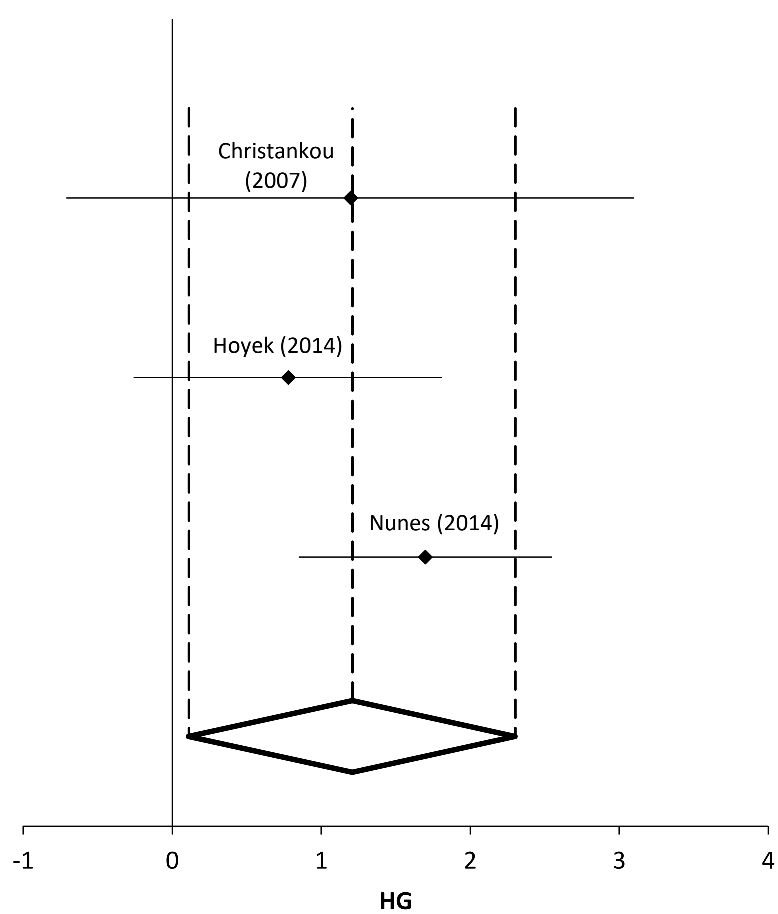
No immobilization: Injury



P.



Q.



R.